GROWING TIMBER TREES WITH STRAIGHT STEMS: AN EXPLORATION OF RELATIONSHIPS BETWEEN MORPHOLOGICAL TRAITS IN SOME BROADLEAVED TREE SPECIES

by

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Abstract

The research described here had two novel aims: first, to assess the morphological characteristics of the regrowth, in particular stem straightness, of juvenile broadleaved trees following coppicing; and second, to investigate why some trees have straight stems and others do not. These questions were investigated by carrying out a series of field experiments in a range of species, age classes and locations.

Coppicing produced rapid regrowth from the stump sprouts of juvenile oak (*Quercus robur*) and sweet chestnut (*Castanea sativa*). Multi-stemming and mortality were not significant. Height regrowth was almost three times faster than the height growth in the uncoppiced trees in the first year following coppicing. Thereafter vigour in the coppice trees declined. After five years there was little difference between the height of the coppiced trees and the height of the uncoppiced trees. The regrowth of the coppiced trees was much straighter than the uncoppiced trees. Branch length was also reduced as a result of coppicing. The improvements in stem straightness declined gradually but after five years the coppiced trees were still significantly straighter than the uncoppiced trees. This is a novel approach to inducing stem straightness in young trees without the need for close spacing.

The coppice experiments suggested that stem straightness was related to branch length. A series of investigations were carried out in juvenile populations of oak, sweet chestnut, ash (*Fraxinus excelsior*) and sycamore (*Acer pseudoplatanus*) to explore relationships between morphological characteristics. The work was extended to semi mature and mature populations of broadleaved trees of various species.

Branch length, tree height and stem straightness were found to be related in all species, age classes and locations. The morphological characteristics of the trees in

the study were proportional to one another. Trees with symmetrical crowns had straighter stems than those with asymmetrical crowns. In trees with asymmetrical crowns those with proportionately shorter branches had straighter stems than trees with long branches. In effect, crown symmetry is the most important single factor that is related to stem straightness in trees. When trees do not have symmetrical crowns, branch length is the most important factor that is related to stem straightness. Finally, a new and practical method of ranking stem quality, based on branch length and stem straightness is presented.

Broadleaved trees with straight stems follow rules of proportionality. This is an original insight into the nature of tree growth.

Contents

1. CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

The forest industry in Great Britain has been expanding since the creation of the Forestry Commission in 1919. Much of this expansion has been due to the establishment and tending of coniferous plantations in Scotland, the North of England and on dry heathland sites in the English lowlands. It is estimated that the production of timber will increase from 4 million cubic metres in the 1970s to 15 million cubic metres by 2020 (Forestry Commission, 1998). The private sector planted 300,998 ha of new forest between 1978 and 1997 (Forestry Commission, 1998). By 1997 the proportion of broadleaved planting compared to coniferous planting in England had increased to approximately 5:1.

The Government has developed policies aimed at sustainable forest management (Forestry Commission, 1991: and HM Government, 1994). These include:

> *'The sustainable management of our existing woods and forests'* and
> *'A steady expansion of tree cover to increase the many, diverse benefits that forests provide.'*

The planned rate of expansion for England is estimated as a doubling of woodland cover within 50 years (HM Government, 1995).

The continued expansion of Britain's forest area includes an expansion of economic value including improvements in the quality of the timber resource. It is the British Government's stated objective to encourage

> *'an increase in the quality and value of timber produced by broadleaved woodlands as a whole'.* (Forestry Commission, 1985).

The expansion of broadleaved planting in Great Britain during the 1980s and 1990s has been achieved at the expense of the recommended planting densities for veneer quality timber for each species. Research has shown that high stocking densities

during the early years of establishment are required to produce veneer quality hardwood timber (Savill and Spilsbury, 1991 and Kerr and Evans, 1993). Crops grown at high densities grow taller and with fewer large branches (Harmer, 1989). The control of lateral bud activity, the development of side branches and the extent of apical dominance can be altered by manipulating crop density. High stocking densities improve the potential for the production of veneer butts due to fewer and smaller knots. In spite of this low stocking densities have become normal practice in Britain because of the prohibitively high cost of achieving recommended planting densities.

Low planting densities require fewer transplants per ha and less labour per ha than high densities. It is unlikely that the current practice of planting broadleaves at low stocking densities, in Great Britain, will facilitate the implementation of government policy on quality and timber value. The projected doubling of woodland cover in England over the next 50 years, if carried out with low stocking densities, will do nothing to improve the situation. Current establishment techniques rely on high initial investments that cannot be justified over the long rotations required to produce veneer quality timber.

The traditional silvicultural system used for growing oak (*Quercus robur* L. *and Q. petraea* (Mattuschka) Liebl.) in Great Britain was coppice with standards. The standard oak trees were widely spaced and developed large crowns due to lack of competition. Where high forest did exist, foresters grew the trees at wide spacing to encourage heavy branching. Evelyn (1664) recommended spacing of not less than 40 feet apart (67 stems ha^{-1}) to allow the crowns to spread. Crooked timbers were popular and were used for many purposes including shipbuilding (Savill and Spilsbury, 1991). For example, Marshall (1803) calculated that the proportion of crooked timbers to straight timbers, used in the construction of ships, was almost two to one. The large, open grown oak trees that are a feature of the British landscape today are remnants of this traditional silvicultural practice.

Coppice with standards was, and remains, an important feature of silvicultural systems in countries such as France, (Ningre and Doussot, 1993). However, oak silviculture, in most of continental Europe including France, has followed a different tradition to that of Great Britain. High forest systems with close spacing have produced trees with long branchless boles (Savill and Spilsbury, 1991). Recommended initial stocking densities in Germany have varied between 7600 stems ha^{-1} (Burckhardt, 1870), up to 15000 stems ha^{-1} during the Twentieth Century.

Savill and Spilsbury (1991) recommend planting densities for oak of 5000 to 6250 stems per ha^{-1}. This is very close to continental practice but also reflects a compromise between high densities and financial constraints. Kerr and Evans (1993) recommend that oak should have an initial density of 3086 stems ha^{-1} for high quality timber production. The Woodland Grant Scheme (Forestry Commission, 1988) accepts initial densities for many broadleaves of 1100 stems ha^{-1}. This minimum density has become the norm in British forestry (Miller *et al*, 1988a and b).

Clear-cutting is now the most common silvicultural system in Britain and Europe. Forests are grown on the basis of fixed rotations, depending on species and site characteristics (Troup, 1928). Forest economists use the concept net discounted revenue (NDR) when assessing forest costs and revenues. (Johnston *et al.*, 1967: . Price, 1976 and 1989). Costs and revenues are discounted at varying interest rates to specific points in time. Thus, decisions concerning the timing of forest operational costs and revenues throughout the whole rotation can be compared with alternative operational strategies. The cost of planting trees at year one, if not offset by early revenues, increases when discounted over the whole rotation. Bartelheimer (1991) concludes that the silviculture of oak can be profitable if the highest quality is sought over long rotations. Long rotations, without regular revenue, increase costs. For conifers it is common to have rotations of 50 years but an oak forest may have a rotation of 200 years. It is therefore, essential that tree establishment is carried out cheaply and efficiently if foresters are to avoid large losses due to discounted costs and revenues.

Attempts to reduce costs have lead to lower planting densities and reduced competition, and thus, poorer potential for the production of high quality timber.

There have been some innovative attempts in Europe to reduce costs and increase competition by novel silvicultural techniques. Near the town of Gray, La Franche-Comte, in France, oak trees have been planted at low planting densities in areas where natural regeneration of hornbeam (*Carpinus betulus*) is prolific (Jamey, 1988). The hornbeam provides severe lateral competition for the oak during the period of establishment. The hornbeam is thinned out until 10-15 years old. The long thin oak poles are then allowed to develop spreading crowns and improved diameter growth. This technique has not been adopted in Britain largely because of the lack of successful natural regeneration of a secondary species.

In Northeast France Jamey (1988) recommends that bands of pure oak should be planted at 1m x 1m and 1.6m x 1.6m spacing by five trees wide. One band of oak is followed by an equivalent ride that remains fallow. This in turn is followed by another band of oak, and so on. The central row of oaks within each band benefits from severe competition and is eventually favoured as the final crop. Similar results have been obtained by planting clumps of oak trees with large areas of fallow land in between. The tree in the centre of each clump benefits from severe competition. In both cases the overall density per hectare is reduced, thus reducing costs, but the final crop trees experience severe local competition. In both cases there have been problems with excessive branchiness and form of the edge trees, around the clumps, and along side the rides, leading to a high proportion of poorly formed trees. Similar systems have been used in the classic oak forests of Northwest France (Tendron, 1983).

Oak has been established in Baden-Wurttemberg at low initial planting densities (Kenk, 1993). The intra-species competition, necessary for the production of high quality timber, has been replaced by naturally regenerated pioneer species. It is claimed that these forests cost no more to establish than coniferous forest. It is not known whether these new techniques will produce high quality timber.

The use of conifers as nurses has been suggested as a method of reducing the cost of establishing broadleaves. Anecdotal evidence from experienced foresters (Darrah and Dodds, 1967), during a discussion of the Wessex Silvicultural Group, produce recommendations that are site specific. In some cases the conifers outgrew the broadleaves and vice versa, depending on genetics, climate, soils, aspect and silvicultural system.

The practice of 'stumping back' is a traditional silvicultural technique used in parts of Britain and Europe. Badly formed stems of young trees are cut back below the deformed part of the stem with the objective of stimulating new, straight regrowth. Very little work has been done to evaluate the effectiveness of this technique as a method of improving the establishment of timber crops and there is little evidence that this technique has been used to improve the form of all stems. This technique should be tested as a method of improving establishment success and quality because it offers the possibility of improving form irrespective of genotype.

It is generally accepted that the process of tree establishment should be completed within five years of commencement (Forestry Commission, 1988). If establishment is delayed beyond this point costs can rise dramatically. Invasions by weeds and pests become much more difficult to control. Delayed establishment produces opportunity costs that effectively extend the rotation length and increase discounted costs. The establishment process includes nursery production, cultivation, planting, weed suppression and pest control. In recent years there have been many gains in efficiency and reductions in cost. There have been many improvements in the quality of nursery seedlings and transplants. In particular physiological stresses and damage to plants, during lifting, handling and transport have been reduced. Assessments of root growth potential have made it possible to review the effects of damage potential of every stage of nursery production, transportation, and planting operation. Losses due to physiological shock have been reduced by improved plant handling techniques (Ritchie and Dunlap, 1980); on loblolly pine (Feret and Kreh, 1985); with cold storage of Sitka spruce and Douglas fir (Cannell *et al.*, 1990); root fibrosity of Sitka spruce (Deans *et al.*, 1990); electrolyte leakage from fine roots of conifer seedlings (McKay,

1992); response of Sitka spruce seedlings to dropping (McKay *et al.*, 1993); effects of stresses between lifting and planting on nursery stock quality and performance (McKay, 1997); seedling survival of shortleaf pine (South and Hallgren, 1997); mechanical shock during transportation (Stjernberg, 1997); safe handling (Tabbush, 1986, 1987a and 1987b).

Selective herbicides have drastically reduced the competition for water in young trees (Williamson, 1991). Other developments such as tree shelters (Tuley, 1985) have improved the success of tree establishment by creating a warm microclimate that surrounds the young trees.

These reductions in cost have not, however, been sufficient to encourage high planting densities. Even though they receive large subsidies, foresters in Britain are not currently producing hardwood crops with high stocking densities (Kerr and Evans, 1993). The high costs of seed production, nursery practice, ground preparation and establishment techniques have encouraged foresters to adopt low stocking densities. Novel methods of tree establishment, which have very low net costs, are essential if investment in veneer quality timber is to be achieved.

Natural regeneration has been suggested as a means of reducing establishment costs. Troup (1928) comments that this method can sometimes take up to 40 years to re-establish a crop. Harmer (1995) concludes that natural regeneration can be successful under the right conditions though he recommends a change in culture of management objectives away from purely timber values. It is unlikely that natural regeneration has a part to play in the establishment of new woodland areas except in cases where there is an edge effect of mature woodland next to the new ground.

Other methods of increasing competition include vegetative reproduction. Researchers studying the effects of coppicing have concentrated on traditional systems producing small diameter timber from multiple stems (Bourne, 1924; Troup, 1928; Busgen and Munch, 1929; Roth and Sleeth, 1939; Morris and Perring, 1974; Crockford and Savill, 1991. These systems were typically concerned with the repeated coppicing of old and relatively large diameter trees.

Most broadleaved trees, if damaged or cut back, will react by producing new shoots. This reaction is thought to be an ecological response to fire, insect damage, drought and other sources of natural disturbance (Morris and Perring, 1974). This characteristic has been used for centuries for silvicultural systems known as coppice and coppice with standards (Troup, 1928). This system produces small diameter timber during short rotations in both temperate and tropical conditions. Coppice with standards is characterised by the development of mature trees from some of the better coppice shoots. A single stem of good form and vigour is selected from a coppice stool and allowed to develop into a mature tree. These stored shoots are known as standards. They may be allowed to grow on for several hundred years. This system produces a wide range of timber sizes that are available for harvest at regular intervals.

The characteristics of vegetative reproduction as a result of coppice treatments are well known. Busgen and Munch (1929) found that shoots sprouting from root collars arose from dormant buds. The pith of these buds could be traced back to the pith of the main stem. The sprouting capacity of the trees reduced with age. Dormant buds can occur at any level of the stem but Roth and Sleeth (1939) report that shoots which sprout above ground level are subject to butt rot. They also found that the incidence of butt rot in oak increased with the diameter of the parent stump. Leffelman and Hawley (1925) noted that butt rot was insignificant on stumps of less than 50 cm because stumps of this size usually callus over before they become infected. Bourne (1924) reported that oak coppice in Germany had been worked over many rotations for centuries without loss of vigour. Trees which are coppiced at a young age and at ground level retain their vigour and are resistant to rot.

Other forms of vegetative regeneration exist but they are of less value in oak coppice systems than of the stump sprouts already described. Adventitious shoots from callus tissue surrounding the cambial layer are less vigorous and prone to rot (Troup, 1928: Woods and Cassaday, 1961). Root suckers and layering techniques cannot be depended upon for oak (Busgen and Munch, 1929), though are useful for other species such as poplar.

In recent times the ability of broadleaved trees to regenerate by coppicing has been exploited by the development of energy crops from juvenile stems of species such as willow and poplar. In the United States Lothner (1991), has assessed the economics of energy plantations: Tuskan and Rensema (1992) investigated differences in poplar clones: Debell and Harrington (1993) evaluated biomass cultural systems including species mixtures. In Scandinavia, Ferm (1993) recommended investigations into the use of natural birch stands as short-rotation energy crops. In Britain and Europe much of this work has been concentrated on high yielding willow (*Salix*) and poplar (*Populus*) species and clones (Cannell *et al.*, 1988: Clay and Dixon, 1993a and b: Royle and Ostry, 1995: Ceulemans *et al.*, 1996). Typically, cuttings are established after ground cultivation and weed control. They are then coppiced after the first year of growth. Each young stool responds by producing several new vigorous shoots. Each stool receives successive coppice treatments every two or three years. Each of these treatments yield wood biomass for energy. After five or six coppice treatments the stools begin to lose vigour and are grubbed out. The process is then repeated with new cuttings. The initial high cost of establishment is recovered quickly by revenues from the early harvest. After the first year of growth the density of the tree canopy suppresses weeds. In spite of this recent work, the use of coppicing techniques on juvenile timber trees such as oak or sycamore has been overlooked.

Crockford and Savill (1991) produced preliminary yield tables for oak coppice and concluded that mean annual increment was similar to those of conventionally spaced plantation oak. These studies were carried out on traditional coppice systems using mature trees. Very little is known about the growth of juvenile timber trees such as oak, following coppicing.

Wood users today favour long straight stems with small knot sizes. The shortage of long straight oak stems in Great Britain has been attributed to the gradual selection in favour of crookedness since Neolithic times (Savill and Spilsbury, 1991). Some evidence exists to support the view that morphological characteristics are determined by genetic factors. Stem straightness, for example, has been found to be strongly heritable (Zobel and van Buijtenen, 1989), as has branch angle (Zobel and Talbert, 1984). Branch size, length and clusters have been found to be less heritable (Zobel and Talbert, 1984).

Environmental and silvicultural conditions can influence stem morphology. In Iphofen forest, in Bavaria, oak is grown as coppice with standards and as high forest. The oak standards have similar morphological characteristics to the open grown oak in Great Britain; that is, short stems with large low crowns. The high forest oak is characterised by long straight stems (Savill and Spilsbury, 1991). Very little experimental work has been carried out relating to tree spacing and oak form though (Bryndum, 1957) and (Mitscherlich, 1953) report that wide spacing leads to low timber heights.

Studies of yield class shed little light on qualitative aspects of tree growth. It is well known and generally accepted that qualitative aspects of tree growth must include reliable assessments of tree morphology (Begbie, 1999). There have been many attempts to evaluate morphological traits in young trees. They include assessments of stem straightness and branch architecture. These methods range from being expensive and time consuming to being cheap and subjective. Begbie (1999) balanced the cost of assessment of morphological traits with the economic importance of those traits. Cundall *et al.*, (1998) describe stem form in young trees by using subjective scales of straightness with quantitative assessments of branch architecture. Studies of crown architecture, however, have been found to be too time consuming (Buck-Sorlin and Bell, 2000a).

Some researchers have explored tree morphology from the point of view of predictive models. Evidence exists to support the concept of interrelated growth characteristics. Arber (1950) and Harper (1977) describe the repetitiveness of both tree structure and individual elements of growth. White (1979) describes trees as having 'distinguishable structures' that are basic units while Wilson (1989) refers to tree branches as 'extension units'. Buck-Sorlin and Bell (2000b) argue that branching order and age structure can influence the growth of 'peripheral branch portions'. These descriptions indicate that a model-based approach to the understanding of tree morphology is valid. In effect, trees may be organised into predictable and repetitive growth units. External effects such as crop density can influence changes in the growth of one or more of these units. A thorough understanding of the relationships

between differing growth units may lead to assessments of stem straightness that are objective and reliable. Very little is known about the morphological traits of juvenile timber trees, such as oak, following coppicing.

Objective methods of assessing form in young trees are essential if silviculturists are to meet government objectives for future timber quality (HM Government, 1994). More importantly perhaps, are the benefits to tree biotechnologists, who require early, objective indicators of future tree form (Feret and Kreh, 1985).

Two areas have been overlooked in the study of broadleaved tree establishment and these are reflected in the aims of the research described here. The first is to discover whether the coppicing of juvenile broadleaved timber trees results in improved growth traits. The second is to develop simple, reliable and predictive allometric models that can be used to describe these traits.

To investigate these questions I have carried out a series of field experiments using a variety of broadleaved tree species, age classes and locations.

1.2 LINES OF INVESTIGATION

1.2.1 The effects of coppicing on stem straightness and vigour in juvenile broadleaved trees

In Chapter Two I investigated possible methodologies to enable the study of stem morphology in broadleaved trees. I tested the feasibility of using coppice techniques to improve the stem form of juvenile sweet chestnut (*Castanea sativa*). I attempted, sometimes unsuccessfully, to develop novel techniques of measurement and comparison. I also compared differences in height growth and stem straightness between coppiced and uncoppiced trees. The information gained provided an insight into some causal factors that can determine stem morphology. It also enabled a better understanding of methodologies required to develop the studies in the following chapters.

In Chapter Three I specifically investigated the effects of coppicing and initial tree spacing on the height growth and stem form of juvenile pedunculate oak (*Quercus robur*) in a designed experiment. Growth was compared following one coppice treatment and two consecutive coppice treatments, using three initial tree spacings. The effects observed in this experiment did little to explain possible growth effects in trees growing in normal forest conditions. The question arose, would the observed effects in the designed experiment occur in normal forest conditions?

In Chapter Four I investigated vegetative regrowth following natural forms of damage to stems, such as rabbit damage. I also investigated the range of ecophysiological factors that might influence vegetative regrowth in normal forest conditions.

1.2.2 A new approach to assessing stem straightness in broadleaved trees

In Chapter Five I investigated the proportionality between growth traits such as stem form and branch length in a range of broadleaved tree species, age classes and locations.

In Chapter Six I investigated relationships between crown symmetry, branch length and stem straightness. In Chapter Seven I discuss the appropriateness of using allometric methods of assessing tree growth characteristics in the context of tree improvement.

2. CHAPTER TWO: THE EFFECTS OF COPPICING ON THE GROWTH CHARACTERISTICS OF SWEET CHESTNUT

2.1 INTRODUCTION

It is well known that most broadleaved tree species will respond to stem damage by regenerating vegetatively from stump sprouts arising from dormant buds (Troup, 1928: Busgen and Munch, 1929: Roth and Sleeth, 1939: Morris and Perring, 1974: Cannell et al., 1988: Ferm 1993. This phenomenon has been used in the technique known as coppicing. Trees are cut down at, or near, ground level. In traditional coppice systems, using species such as pedunculate oak, the resulting vegetative regrowth is used as small diameter timber. Many rotations can be obtained over periods of hundreds of years. More recently, plantations of willow or poplar have been coppiced soon after establishment. The vegetative regrowth from these juvenile trees is then used as wood biomass for energy production. Coppicing techniques have not been used to establish veneer quality crops except in the system known as coppice with standards.

Troup (1928) describes how, in coppice with standards, the best stem on a coppice stool (stump complex) can be singled out and encouraged to develop into a mature tree. These 'stored' stems are produced from old stumps containing many stems. No attempt has been made to 'store' stems from vegetative regrowth produced as a result of coppicing newly established juvenile plants.

In this chapter I assessed the response of juvenile sweet chestnut (*Castanea sativa*) to coppicing.

2.2 MATERIALS AND METHODS

2.2.1 Experimental design

Exploratory assessments of tree growth characteristics were taken at the Riseholme Estate, in the Spring of 1997, using part of a provenance trial of *Castanea sativa* established by the Forest Research Agency in 1992. This trial comprised of three blocks, each one containing six plots. Each plot contained 36 trees of one provenance planted at 2.0m x 2.0m spacing in a configuration of 6 x 6 trees. There were therefore six provenances replicated three times throughout the area. Each plot was dissected into two split-plots of 3 x 6 trees. One split-plot was coppiced and the other was left uncoppiced. The coppice treatments were applied in April 1996 and the first measurements were taken immediately and again in March 1997, following a full growing season. Details of provenances can be seen in Appendix A.

2.2.2 Measurements taken

a) Height

Height (cm) was compared between coppiced and uncoppiced trees in April 1996 immediately following the coppice treatment. This was repeated after one growing season in March 1997, March 1998 and March 2000. Measurements were carried out using a one metre steel ruler. They were taken from ground level at the base of the tree to the highest point of the tree. Trees with bent stems were not straightened. Measurements were rounded down to the nearest centimetre. It was estimated that due to the inherent errors of the measurement technique, the true measurement could be + or – 2.0 cm of the recorded measurement. This is in line with accepted practice (Cundall *et al.*, 1998).

b) Buds

The length and diameter of the terminal bud of each stem measured in millimetres were compared between the coppiced and uncoppiced trees. These measurements were taken using digital calipers in April 1996.

c) Straight Length

Straight length was estimated as the length of straight stem, measured from the root collar or ground level, whichever is highest, to the point where the main stem

becomes indistinguishable or springs into the crown or deviates from straightness. These measurements were made in March 2000. Straightness was estimated following guidelines for the measurement of green sawlogs (Forestry Commission, 1990). A theoretical line drawn from either end of a length of stem, starting and finishing at the centre of the pith, should not deviate outside the actual stem by more than a stem width. Slight bowing outside these limits is acceptable but angular deviations are not. The measure of straightness, therefore, is the length of the butt end that falls within these limits, rounded down to the nearest centimetre.

Straight length differs from Timber Height (Hamilton, 1975) in that the latter takes no account of deviations in the stem. It should be noted that the straight lengths measured in these experiments cannot necessarily be described as timber as defined as a minimum length of 1.3m and a minimum top diameter of 7 cm (Hamilton, 1975).

d) Longest Branch

These measurements were taken in March 2000. For reasons of economy and practicality I decided to minimise the number of measurements of branches on any one tree. Measurements of every branch include assessments of sub-branches. Each individual measurement is prone to error because decisions have to be made, in each case, where to measure from and where to measure to. As branches become smaller these decisions become more subjective.

It was essential to limit the number of observations to the most influential branches. Attempting to measure all branches would be time consuming and prone to compounded measurement errors. The ensuing statistical analysis would be overly complicated and inefficient. Little would be gained by following such a course. I assumed that if branch length were related to stem straightness then all branches would probably have an influence but it was likely that long branches would have more influence than smaller branches. Long branches exert more leverage on the stem than short branches and they usually have larger diameters at the axil. It was pragmatic to measure the length of the longest branch on each tree because such a branch would probably be more influential than lesser branches. This novel approach could always be abandoned if it proved to be irrelevant. *Longest branch* is defined as the length of the longest branch of a tree measured from the axil to the tip of the

branch.

2.2.3 Treatments

Within each plot, the trees in one split-plot were coppiced and the trees in the other split-plot were left uncoppiced. Coppicing was carried out using a petrol powered clearing saw. The trees were cut down as close to ground level as possible.

2.2.4 Statistical analysis

The analysis of variance procedure was used as the basis for the main method of analysis. This is a technique that separates variation into separate independent components. This is done by testing that population means are equal. The separate independent components can then be ranked in order of importance. Designed variation can also be separated from experimental error and random effects. Using SAS software, a dependent variable, for example height, is measured against classification variables such as treatments. When the number of dependent variables is equal for each combination of classification variables the design is considered to be balanced and the results valid (SAS Institute, 1998). When the design is not balanced, as was the case in these experiments due to mortality, valid results can be produced using the Generalised Linear Models, based on regression analysis.

The hypothesis testing was achieved by the use of Type 1 Sums of Squares which are model dependent; each effect being adjusted only for the preceding effects of the model (SAS Institute, 1998).

In these studies the verification of assumptions required for analysis of variance calculations included residual analysis, checks for normal distribution, checks for independence and checks for constant variance. The data met these assumptions.

2.3 RESULTS

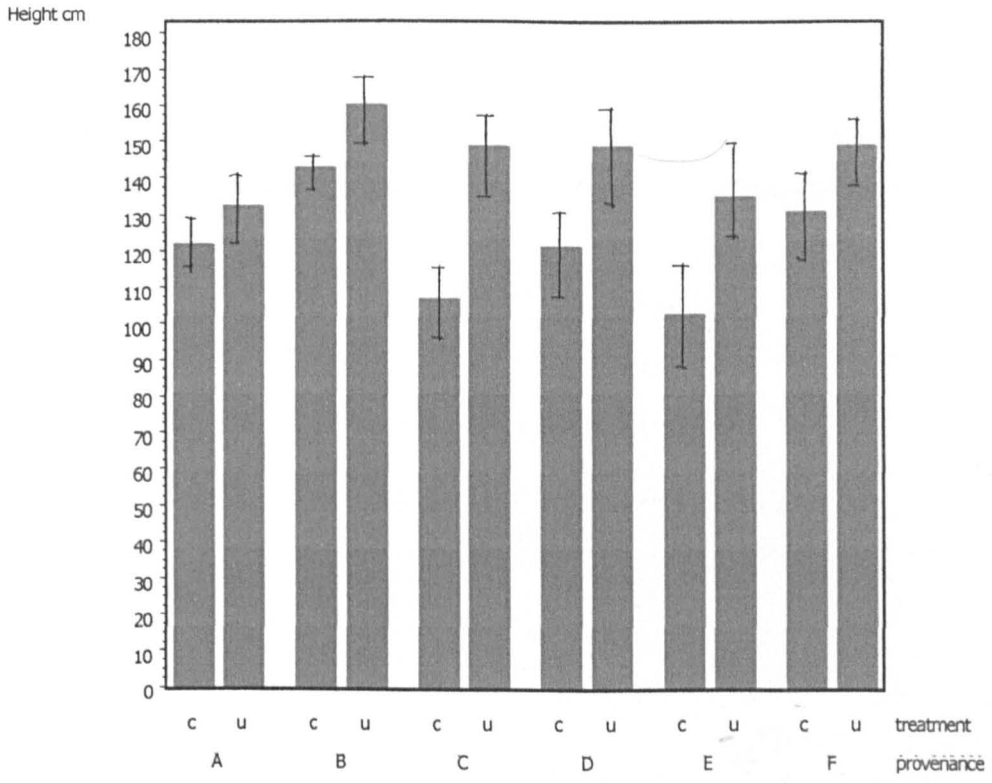
2.3.1 Height effects

A summary of results is shown in Table 2.1 and Figure 2.1. Coppicing had no effect on the mean *height* of the trees after two growing seasons (post coppicing) but did have an effect after four seasons. The mean *height* of the coppiced trees was 125cm compared with 146cm for the uncoppiced trees after four seasons (F Value = 24.36, $P < 0.0001$). Results are also shown in Table 2.1 for the six provenances. Differences in *height* only became apparent after four seasons in three of the provenances. The trees responded to the coppice treatments by increased incremental *height*.

Table 2.1 Summary of results of the effects of coppicing on the height of sweet chestnut measured in March 1997, March 1998 and March 2000

Measurements	Number	Coppiced	Uncoppiced	P <
Mean Height in March 1997				
All trees	216	57.cm	64cm	ns
Provenance A	36	39cm	54cm	ns
B	36	65cm	79cm	ns
C	36	50cm	56cm	ns
D	36	52cm	36cm	0.0232
E	36	61cm	65cm	ns
F	36	71cm	89cm	ns
Mean Height in March 1998				
All trees	216	85cm	91cm	ns
Provenance A	36	60cm	73cm	ns
B	36	98cm	108cm	ns
C	36	79cm	79cm	ns
D	36	65cm	60cm	ns
E	36	97cm	91cm	ns
F	36	104cm	125cm	ns
Mean height in March 2000				
All trees	472	124cm	145cm	0.0001
Provenance A	75	121cm	132cm	ns
B	84	145cm	160cm	ns
C	74	110cm	148cm	0.0029
D	76	127cm	148cm	ns
E	77	105cm	135cm	0.0110
F	86	130cm	148cm	0.0492

Figure 2.1 **The effects of coppicing on height in six provenances of sweet chestnut after four growing seasons.**



Error bars shown at ± 2 S.E.

C = Coppiced

U = Uncoppiced

F Value = 24.36, $P < 0.0001$

2.3.2 Buds

Attempts to assess bud size and shape were unsuccessful. It was found that there were too many variables within the shape of the buds to develop a reliable methodology. It was extremely difficult to measure the same features in the same place on each bud. These problems were compounded by frost damage suffered by the swelling buds in June 1996. Preliminary investigations indicated that finding an objective non destructive method of assessing bud size and shape was unlikely to be achieved in sweet chestnut.

2.3.3 Straight length

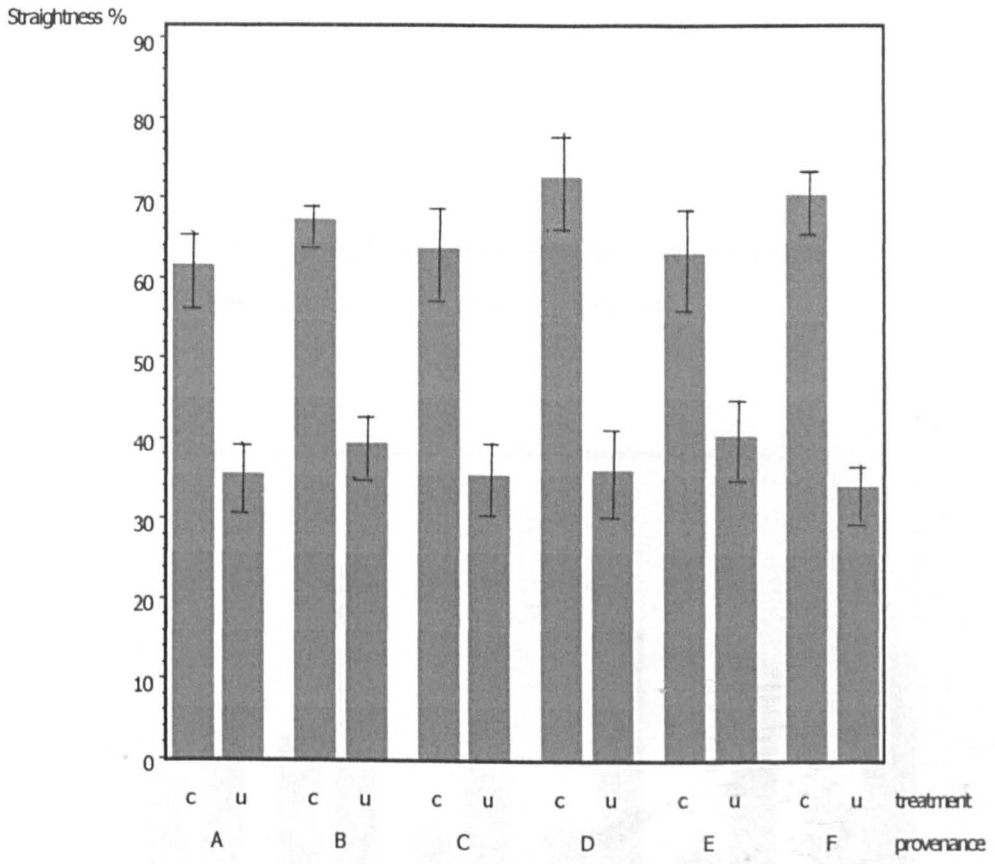
The coppiced trees appeared to have straighter stems than the uncoppiced trees but an objective method of assessing straightness was not available until after the fourth growing season following the coppice treatments. A summary of the effects of coppicing on stem straightness can be seen in Table 2.2. The mean *straight length* of the coppiced trees was greater than the uncoppiced trees. The mean *straight length* for the coppiced trees was 82cm compared with 47cm for the uncoppiced trees, (F Value = 72.78, $P < 0.0001$). Table 2.2 shows similar results for each provenance. *Straight length* was also expressed as a percentage of the height of the tree. Thus, it can be seen in Table 2.2 and Figure 2.2 that for all trees *straightness percentage* was 77% for the coppiced trees compared with 51% for the uncoppiced trees, (F Value = 102.90, $P < 0.0001$).

Table 2.2 Summary of results of the effects of coppicing on *straight length* and *straightness percentage* *

Measurements	Number	Coppiced	Uncoppiced	P <
Straight Length in March 2000				
All trees	641	82cm	47cm	0.0001
Provenance A	108	76cm	41cm	0.0013
B	106	96cm	55cm	0.0001
C	106	71cm	44cm	0.0138
D	106	87cm	47cm	0.0001
E	107	66cm	45cm	0.0276
F	108	91cm	47cm	0.0001
Straightness percentage in March 2000				
All trees	641	77%	51%	0.0001
Provenance A	108	75%	52%	0.0006
B	106	73%	53%	0.0022
C	106	80%	49%	0.0001
D	106	82%	50%	0.0001
E	107	75%	53%	0.0012
F	108	76%	47%	0.0001

* The coppice treatments were applied in April 1996

Figure 2.2 The effects of coppicing on straightness percentage in six provenances of sweet chestnut after four growing seasons.



Error bars shown at ± 2 S.E.

C = Coppiced

U = Uncoppiced

F Value = 102.90, $P < 0.0001$

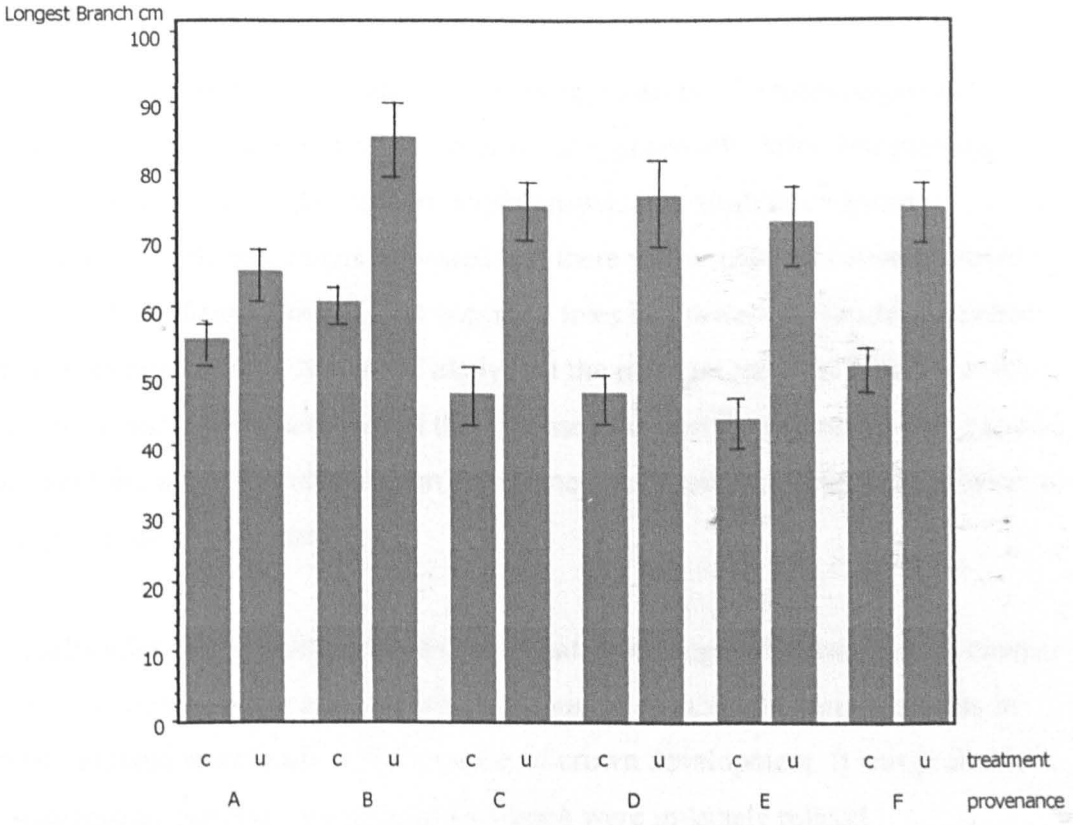
Coppicing caused significant differences in *straightness percentage* after four growing seasons. There were no differences in *straightness percentage* as a result of differences in provenance.

2.3.4 Longest Branch

The effects of coppicing on *longest branch* can be seen in Figure 2.3. Coppicing caused significant differences in the length of mean *longest branch.* The mean *longest branch* for the coppiced trees was 51cm compared with 75cm for the uncoppiced trees, F Value = 59.72, $P < 0.0001$.

There were no differences in *longest branch* as a result of differences in provenance.

Figure 2.3 The effects of coppicing on longest branch in six provenances of sweet chestnut after four growing seasons.



Error bars shown at ± 2 S.E.

C = Coppiced

U = Uncoppiced

F Value = 59.72, $P < 0.0001$

2.4 DISCUSSION

The preliminary studies, after the first two growing seasons, produced many useful results, some of them negative in the case of buds, which provided an indicative starting point for future experimental methodologies. The rate of multi stemming, though not formally assessed was very low and appeared much less than would have been expected in willow or poplar. This was unexpected.

Stem straightness was not assessed formally after two years but it did appear to be positively affected by the coppice treatments. It was clear that there was a need for an objective method of assessing stem straightness. This was developed and assessed after the fourth growing season.

Coppicing did not affect *height* after two growing seasons. The trees responded quickly to coppicing by improved incremental height growth. After four growing seasons there was a slight decrease in *height* growth as a result of coppicing. Observations of individual trees indicated that there was a trade off between crown development and *height* growth. The coppiced trees had fewer and shorter branches than the uncoppiced trees. It seemed likely that the rapid incremental *height* growth following coppicing was achieved at the expense of crown development. The question arose: were the improvements in stem straightness, as a result of coppicing, related to the sparse crown development?

The results after four growing seasons show that coppicing had caused improvements in *straightness percentage* and a decrease in *longest branch*. The improvements in stem straightness were made at the expense of crown development. It was probable that *straightness percentage* and *longest branch* were inversely related.

3. CHAPTER THREE: THE EFFECTS OF COPPICING ON THE GROWTH CHARACTERISTICS OF JUVENILE OAK TREES

3.1 INTRODUCTION

The results of the preliminary studies on sweet chestnut, after four growing seasons, indicated that it was possible to coppice juvenile trees without increasing the risk of mortality. Coppicing also appeared to affect tree growth. The immediate regrowth of stems in the coppiced trees was straighter than in the uncoppiced trees. It was necessary to extend the study in a designed experiment in order to differentiate between the possible effects of coppicing and other sources of variation.

In this chapter I describe the planning, establishment and implementation of a major experimental area using pedunculate oak *(Quercus robur)*. Five treatments were used. These consisted of two coppice treatments and three tree spacing treatments.

3.2 MATERIALS AND METHODS

3.2.1 Plant establishment

Acorns were collected from mature unregistered pedunculate oak (*Quercus robur)* from the Riseholme estate in 1995. The local environmental constraints existing on the Riseholme site include very late frosts and high soil pH (7.8). Very little direct evidence exists to support the view that oak from registered seed sources are adversely affected by late frosts. Evidence, however, from provenance trials of sycamore *(Acer pseudoplatanus)* on the same site indicate that provenances with early bud burst are more prone to frost damage (Cundall *et al.*, 1998). The registered seed sources available for oak come from areas much further south than the Riseholme phenotype. Observations of the mature oak on the Riseholme estate indicated that healthy specimens can be grown in soils with a higher pH than is usually recommended for the species. I decided to use the phenotype from the local origin because I considered that there was a lower risk from frost damage and a lower risk of ill health manifested by chlorosis, than trees from registered sources.

After germination in 1996, the oak seedlings spent one year in a seedbed. They were kept weed free but were not fertilised or irrigated. The seedlings were then to be transferred to the planting site. Unfortunately, the original planting site became unavailable because archaeological remains were discovered on it. An alternative site could not be found quickly. Rather than abandon the study it was decided to transfer the seedlings into plant pots until an alternative planting site could be found. The seedlings were transferred to 15 cm rose pots, containing Irish moss peat, early in 1997. This was done in preference to allowing the seedlings to grow for another year in the seedbed. When bare rooted stock is removed from the soil there is a certain amount of physiological shock to the plant (MacKay, 1997). This can result in minimal height growth and crown development in the first year after planting. The newly planted trees often 'sit' for the first year with minimal growth. It has been demonstrated that trees that have been placed in pots can be transferred later to the planting site with minimal shock. As long as the root systems do not become pot bound, growth within the pot will be unaffected and subsequent root development at the eventual planting site will not be restricted.

No fertiliser was added to the trees but they received frequent irrigation. Rose pots were used in preference to ordinary plant pots because they are both narrow and deep. Deep pots were required to allow for adequate taproot development. Narrow pots were required to reduce the amount of peat needed to fill them. It was important to keep costs to a minimum. By using narrow pots less peat was required overall and less space was required for storage. The narrow pots were also easier to transport to the planting site than wide pots and easier to handle at every stage of the operation. Fertiliser was not used but there were no visible signs of distress from the seedlings and no losses whatsoever. Irish moss peat was used because of its low cost. The pH of the soil in the seedbed was between 7.5 and 7.8 while the pH of the peat was 4.5. The seedlings tolerated the change in pH from the seedbed to the peat without any apparent ill effects on health or growth.

3.2.2 Sources of site variation

The area for the current study was selected at Riseholme estate from fallow ground that lay alongside four established provenance trials. An irregular four sided polygon of approximately 42m x 57m was available between the provenance trials and the boundary fence. This area was fenced to protect against rabbits.

The design of the experimental area took into account the following potential constraints and sources of variation:

a) ***Exposure and forest influence***

The eastern edge of the study area was bordered, within four metres, by mature broadleaved forest. Natural regeneration of oak, sycamore *(Acer pseudoplatanus)* and ash *(Fraxinus excelsior)* were evident in the study area before cultivation and planting. The incidence of natural regeneration was inversely proportional to the distance from the mature crop. The northern boundary of the study area comprised a field of newly established ash and an area of agricultural set-aside. This aspect was relatively exposed. To the south and west the study was protected from the prevailing wind by mature forest.

b) Soil

Soil pH ranged from 7.5 to 7.8 across the study area. The moisture content appeared to vary very little. Weed growth was slightly more luxuriant in some places than in others. It is not known whether these differences were due to variations in moisture content or other factors. Soil depth varied from 20 cm to 140 cm, the underlying bedrock being Jurassic limestone.

c) Slope

The study area has a slight slope that starts from the northeast corner of the plot and falls away towards the southwest corner. The slope is convex and ranges from 1% in the northeast to 4% in the southwest. Late frosts can occur in June.

d) Weed cover

There were minor differences in the extent, type and density of weed cover. No attempt was made to map out the area accurately by weed type, either by individual species or by groups of species because variation did not follow any particular gradient. It was accepted that there might be a slight influence on individual tree growth as a result of the type and density of weed species. It was decided to take account of this source of variation by the overall experimental design. The following weed species were recorded in December 1996.

Arctium minus	(Lesser Burdock)
Arctium lappa	(greater burdock)
Senecio jacobaea	(ragwort)
Bellis perennis	(daisy)
Impatiens noli-tangere	(touch-me-not balsam)
Impatiens glandulifera	(Himalayan balsam)
Stellaria media	(common chickweed)
Alopecurus pratensis	(meadow fox-tail grass)
Epilobium angustifolium	(rosebay willowherb)
Taraxacum officinale	(dandelion)

Assorted grasses and mosses.

e) Mycorrhiza

Some of the containerised plants showed evidence of mycorrhizae at the time of planting. No attempt was made to quantify this. The tree planters were unaware of the phenomenon and so paid no attention to it. The tree planters were also unaware of the location of treatment plots and control plots. The tree planters made no attempt to actively select planting site for individual trees based on the incidence of mychorrizas.

f) Site preparation

A motorised auger was used in January 1997 to prepare the study area for planting. Preliminary soil depth samples suggested that the underlying limestone bedrock might have been disturbed by the use of cultivation techniques involving ploughs or sub-soilers, bringing limestone to the surface, and increasing alkalinity in localised places. Holes were dug with the auger, 20cm in diameter by approximately 30cm deep. The

auger produced cultivated holes in which to place the containerised trees. It was found that the previous caution shown about using ploughing techniques was unfounded. The auger did not encounter any bedrock but did unearth small pieces of limestone that were found occasionally within the soil profile.

At the time of planting in March 1997 the holes were back filled by up to 10 cm with some of the loose soil upturned by the auger. The trees were then removed from their containers and placed in the holes. They were then "heeled in", where necessary with the addition of more loose soil. The amount of loose soil used, varied and was determined by the relative sizes of the root balls and the depth of the holes.

As each tree was planted a variable amount of soil was left surrounding the planting position. This soil became compacted very quickly and gave the impression that the planting positions had been screefed prior to the planting operation. Screefing has been defined as *...paring of low and surface vegetation, together with most of its roots, to expose a weed free soil surface...* (Ford-Robertson, 1971). The screefing effect provided some protection from weed competition early on in the first growing season post planting. The diameter of the screefed area around the trees ranged from 10 to 50 cm. The depth of the compacted soil was also variable, as was the degree of compaction between each planting position. It was accepted that there might have been a variable amount of weed control because of the screefing phenomenon but the importance of this source of variation did not warrant further quantification until the analysis of the results.

3.2.3 Experimental design

An outline of the experimental area can be seen in Figures 3.1, 3.2, 3.3 and 3.4. A Latin square design was chosen because variations in slope and exposure occurred in two definite directions, in slope from northwest to southeast, in exposure from north-east to south-west. The effect of random variation within the site was accounted for by the use of interrow and intercolumn data. These were used as class variables.

The design had the following characteristics:

A 3x3 Latin square of nine main plots.	729 trees
Each main plot was itself a Latin square of nine sub-plots.	81 trees
Each sub-plot contained nine trees.	9 trees

3.2.4 Treatments

The trees were planted at three spacings (planting densities). These were 1.0m x 1.0m, 1.2m x 1.2m and 1.8m x 1.8m.

One third of the trees were coppiced immediately after planting and then again after the first growing season. These received no further treatments. One third of the trees were left uncoppiced. These were the controls.

The Latin square design was of the split-plot kind. The treatment for the main plot was the initial plant spacing, whereas the sub-plots tested the coppice treatments.

Figure 3.1 Outline of juvenile oak experimental area showing layout of latin square

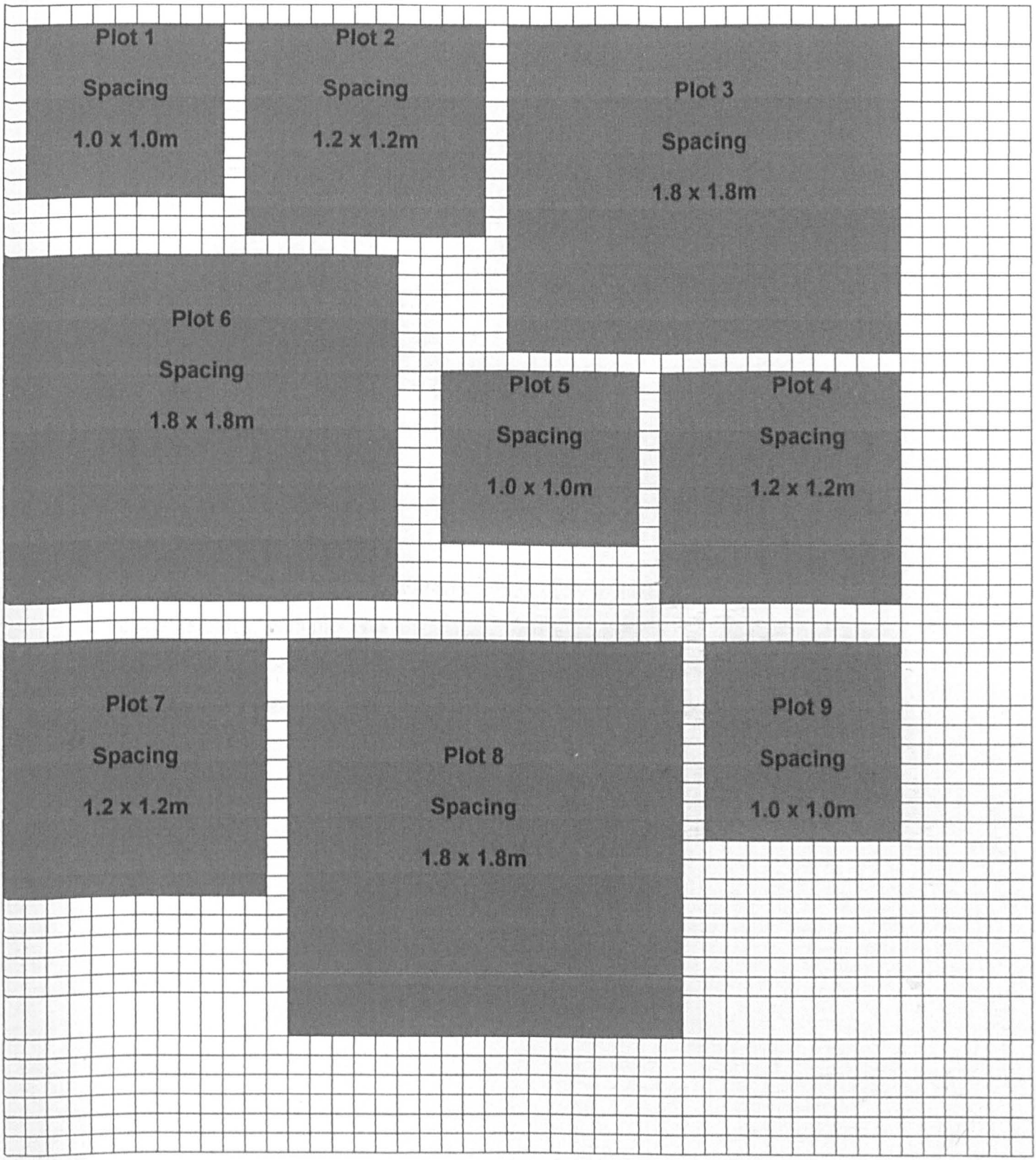
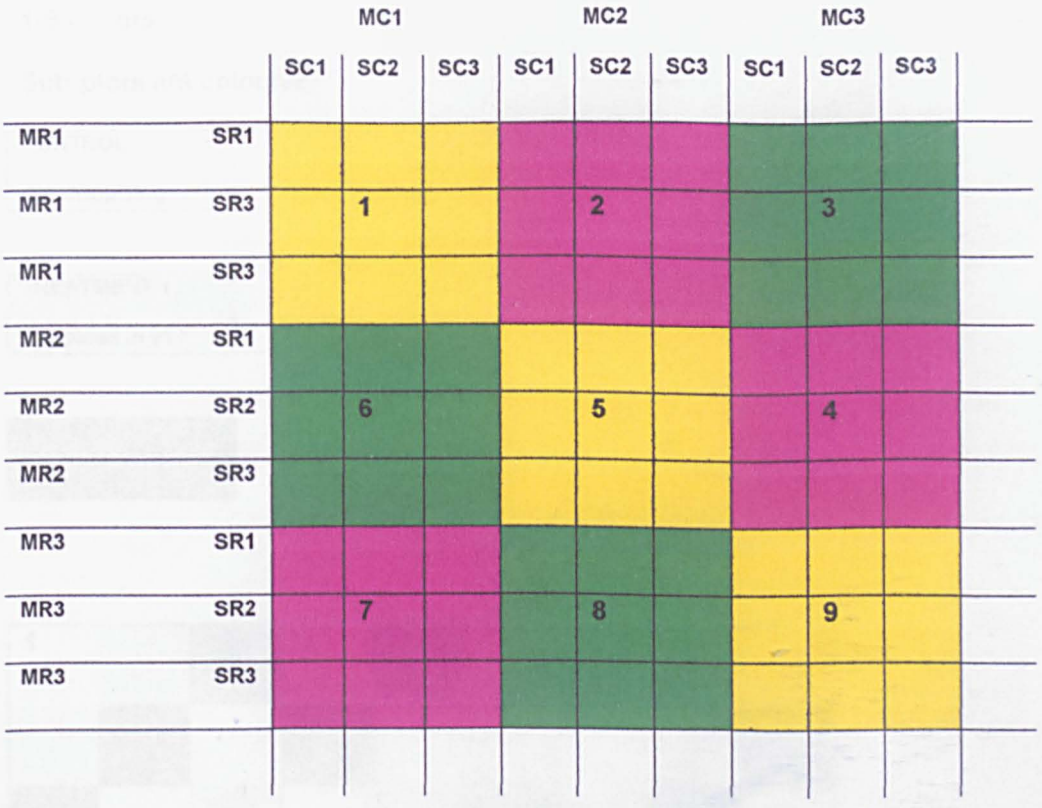


Figure 3.2 Experimental area showing main plots

	Main Column 1	Main Column 2	Main Column 3	
Main Row 1	Plot 1 Small	Plot 2 Medium	Plot 3 Large	
Main Row 2	Plot 6 Large	Plot 5 Small	Plot 4 Medium	
Main Row 3	Plot 7 Medium	Plot 8 Large	Plot 9 Small	

In order to test efficiently the effects of the coppicing treatments on growth characteristics, each plot was assigned co-ordinates according to treatment locations. These locations are classed as sub-plots and accordingly given the legends SR and SC. These are then used as class variables to separate random effects from those of the treatments.

Figure 3.3 Experimental area showing sub-plots



MC = MAIN COLUMN: MR = MAIN ROW: SC = SUB-COLUMN: SR = SUB-ROW

Figure 3.4 Study area - showing treatments

(Spacing is not to scale)

KEY

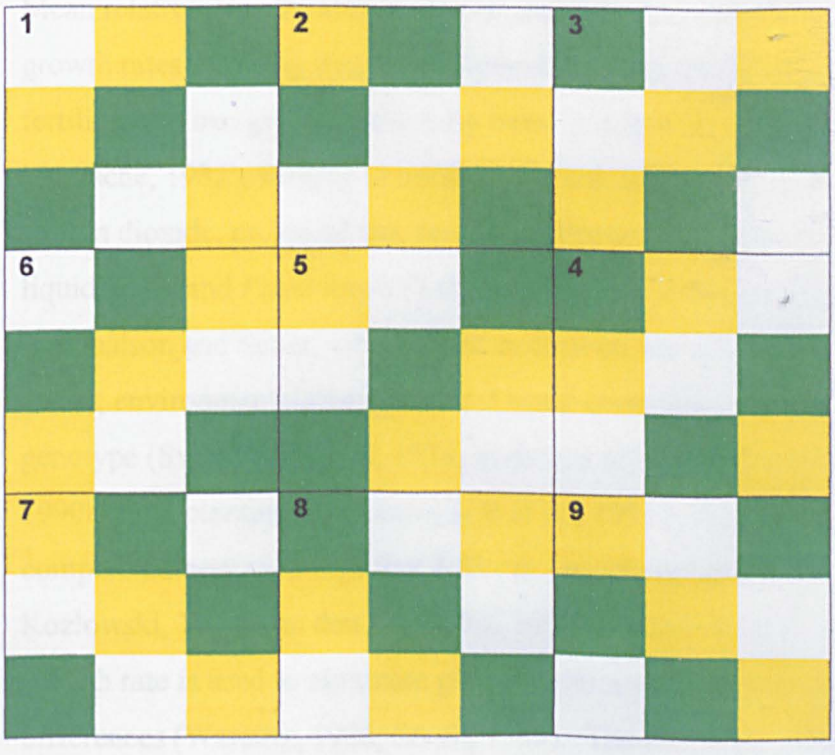
1-9 = Plots

Sub-plots are coloured

CONTROL
No Coppicing

TREATMENT 1
Coppiced in y1 *

TREATMENT 2
Coppiced y1 & y2



* Coppiced y1 only

3.2.5 *Measurements taken*

a) Height

The *height* growth (cm) was compared between coppiced and uncoppiced trees after planting in 1997 and at the end of each growing season in 1998, 1999 and 2002. This was achieved using a one metre steel ruler. Measurements were taken from ground level at the base of the tree to the highest point of the tree. Trees with drooping leading shoots or bent stems were not straightened. Measurements were rounded down to the nearest cm. It was estimated that due to the inherent errors of the measurement technique, the true measurement could be + or – 1 cm of the recorded measurement. This is in line with accepted practice (Cundall *et al.*, 1998). *Height* in these experiments is expressed as the overall height at any time but also as the incremental height in any one year. A discussion on the relevance of incremental height and relative growth rates can be seen below.

Mean relative growth rates are one of the most frequently used methods of assessing growth rates of young trees. The method has been used to assess the effects of fertilisers on tree growth, with tulip trees (Madgwick, 1971); Douglas fir (van den Driessche, 1982), shading in northern red oak and poplar (Kolb and Steiner, 1990a), carbon dioxide, on boreal tree seedlings (Brown and Higginbotham, 1986; liquidamber and *Pinus taeda* (Tolley and Strain, 1984; red spruce seedlings (Samualson and Seiler, 1993), weed control on loblolly pine (Byrne and Wentworth, 1988); environmental conditions and weed control on conifers (Brand, 1991); genotype (Sweet and Wells, 1974; genotype of northern red oak (Kolb and Steiner, 1990b), and planting stock size (Britt *et al.*, 1991). The technique is often used to compare nursery seedlings that differ in size (Sweet and Wareing, 1966; Kramer and Kozlowski, 1979; van den Driessche, 1991; Kozlowski *et al.*, 1991). Relative mean growth rate is used to eliminate growth differences that arise from initial size differences (Wareing, 1966; South, 1995). The technique is based on the theory of compound interest law (West *et al.*, 1920; Snedecor and Cochran, 1971; Kramer and Kozlowski, 1979; Hunt, 1990). The compound interest law can be defined as: ... *the amount of growth made in a unit of time is a constant percentage of the size of the plant at the beginning of the period and the constant percentage does not change with*

size (e.g. is independent of size)... (South, 1995)

Models that depend on relative growth rates assume that tree growth has a constant exponential form. South (1992 and 1995), has warned that over reliance on the concept of relative growth rates can prove to be an oversimplification of actual growth rates. In cases where growth characteristics do not follow the compound interest law the use of relative growth rates may lead to faulty conclusions.

Examinations of genotypes have demonstrated that the relative growth rates of seedlings can be an inappropriate method of assessing early growth. Large genotypes exhibit smaller relative growth rates than smaller genotypes. Research by Burdon and Sweet (1976) has indicated that relative growth rates are an unreliable means of eliminating initial size effects.

The concept of a variable interest rate has been put forward as an alternative model of seedling growth (South 1995). It can be defined as: *...the amount of growth made in a unit of time is a percentage of the size of the plant at the beginning of the period and this percentage changes as the plant increases in size... (South, 1995)*

Incremental growth rates, based on the variable interest law, have been used successfully to examine the growth of *Pinus taeda* seedlings over a 30 year period (South *et al.*, 1988); to compare growth responses to mycorrhizal inoculation (Marx *et al.*, 1988); that growth response at age five was due to the initial difference in growth (Mexal and South, 1991); and to compare growth responses as a result of fertilisation (Auchmoody, 1985). Despite this evidence many researchers continue to use relative growth rates as the primary method of eliminating initial size effects (South, 1995).

It is clear that some doubt exists as to the validity of using relative growth rate as a model in all situations. In cases where ontogenetic drift causes exceptions to the overall model, a more cautious approach should be taken which includes an assessment of actual growth rates. The treatments in the experiments described here involved cutting the trees down to ground level and comparing the subsequent growth with that of the controls. A model based on relative growth rates was not appropriate for the treatments because the initial tree size, 0 cm, was the result of artificial trauma

rather than biological growth.

b) Straight length

Straight length was estimated as the length of straight stem, measured from the root collar or ground level, whichever is highest, to the point where the main stem becomes indistinguishable or springs into the crown or deviates from straightness. These measurements were taken in march 1998, 1999 and 2002. Straightness was estimated following guidelines for the measurement of green sawlogs (Forestry Commission, 1990). A theoretical line drawn from either end of a length of stem, starting and finishing at the centre of the pith, should not deviate outside the actual stem by more than a stem width. Slight bowing outside these limits is acceptable but angular deviations are not. The measure of straightness, therefore, is the length of the butt end that falls within these limits, rounded down to the nearest centimetre.

Straight length differs from timber height (Hamilton, 1975) in that the latter takes no account of deviations in the stem. It should be noted that the straight lengths measured in these experiments cannot necessarily be described as timber as defined as a minimum length of 1.3m and a minimum top diameter of 7 cm (Hamilton, 1975).

3.2.6 Statistical analysis

Two types of software were available for the planning of the experimental design and the statistical analysis of the results. These were Microsoft Excel and SAS. In a review of a selection of statistical software available Binquet, *et al.* (1998) rank software according to fitness for purpose and quality assurance. Software such as Microsoft Excel are categorised as easy to use but with limited functions: software such as Minitab are described as simple reference software that perform most statistical analyses: software such as SAS are described as complex reference software with excellent potential for quality assurance. Knusel (1998) analysed the numerical computations of Microsoft Excel and found them to be inaccurate. He warns statisticians against using it for scientific purposes. SAS was chosen.

SAS programs such as SAS/INSIGHT and SAS/LAB can create exploratory graphics that plot relationships and detect influential observations (SAS Institute, 1998). Federer and Wolfinger (1998) report the ability of SAS to analyse complex random effects such as interrow, intercolumn and intergradient information. Procedures such as Generalised Linear Models (PROC GLM) can separate genuine effects from background noise within complex data sets.

The nature of field trials is such that not all forms of variation can be excluded or accounted for at the outset. In this set of experiments strict uniformity of site conditions, including soils, weed cover, genetics, etc. was not achieved but did not seem to be excessive. SAS was chosen as the most appropriate software available because it was able to take account of any background noise and random effects.

The analysis of variance procedure was used as the basis for the main method of analysis. This is a technique that separates variation into separate independent components. This is done by testing that population means are equal. The separate independent components can then be ranked in order of importance. When the number of dependent variables is equal for each combination of classification variables the design is considered to be balanced and the results valid (SAS Institute, 1998). When the design is not balanced, as was the case in these experiments due to mortality, valid

results can be produced using PROC GLM.

The Latin square design was of the split-plot kind. The treatment for the main plot was the initial plant spacing, whereas the sub-plots tested the coppice treatments. Interactions between the coppice treatments and initial plant spacing were also tested. The error mean square for the main plots was separated from that of the sub-plots and separate F tests conducted within the main analysis.

The hypothesis testing was achieved by the use of Type 1 Sums of Squares which are model dependent; each effect being adjusted only for the preceding effects of the model (SAS Institute, 1998).

In these studies the verification of assumptions required for analysis of variance calculations included residual analysis, checks for normal distribution, checks for independence and checks for constant variance.

3.3 RESULTS

3.3.1 Height

A summary of the effects of coppicing and spacing on *height* after one growing season can be seen in Table 3.1. The mean *height* of the uncoppiced trees was 37cm compared with 31cm in the coppiced trees (F Value = 63.42, $P < 0.0001$). The *height* increment (growth that year) of the coppiced trees was almost three times that of the uncoppiced trees. Coppicing induced rapid *height* growth in the first growing season. Spacing had a small effect on *height* (Table 3.1) after one growing season following coppicing. For 1m x 1m spacing *height* was 35cm, compared with 32cm for 1.2m x 1.2m spacing and 31cm for 1.8m x 1.8m spacing (F value = 10.38, $P < 0.0001$).

Table 3.1 Juvenile oak experiment - Summary height in March 1998

Variable	Trees	Treatments	P	P <
	722	Coppice	Uncoppiced	
Mean height		31cm	37cm -	0.0001

Variable	Trees		Spacing		P <
	722	1.0m	1.2m	1.8m	
Mean height		35cm	32cm	31cm	0.0001

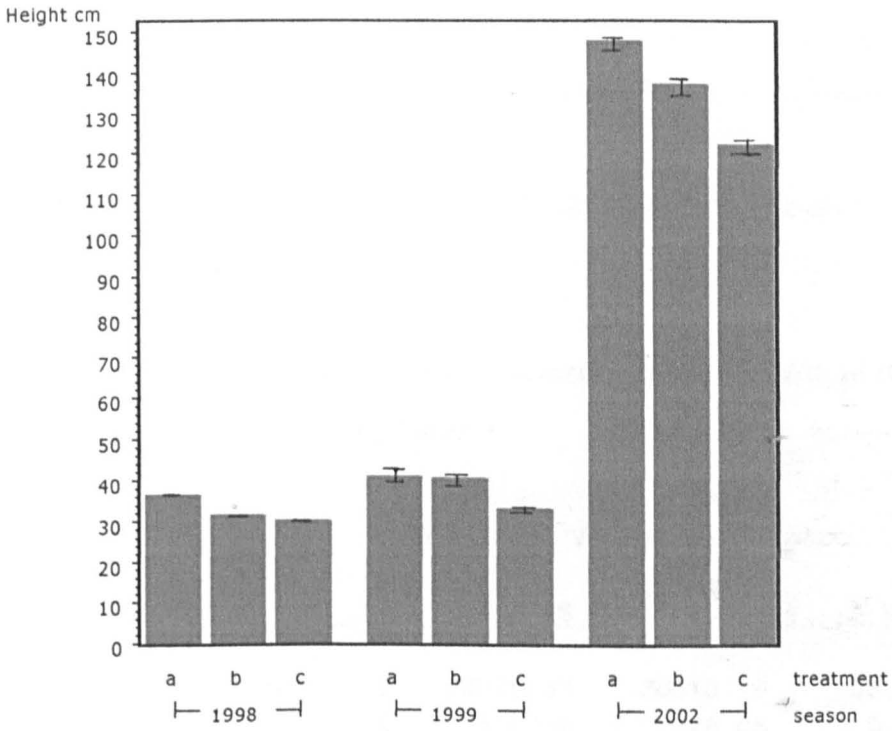
Table 3.2 shows the effects of coppicing on *height* after two growing seasons. There is no significant difference in *height* between the uncoppiced trees and the trees that were coppiced once. The trees that were coppiced twice responded with rapid *height* regrowth of 33cm, but not enough to catch up on the uncoppiced trees and trees coppiced once. There is a slightly significant difference between the coppiced trees and the uncoppiced trees, $P < 0.03$.

Table 3.2 Juvenile oak experiment - Summary of height March 1999

Variable	**Trees**	**Treatments**		
	75	**Coppice 1**	**Coppice 2**	**Uncoppiced**
Height		41cm	33cm	41cm

The effects of coppicing on *height* after five growing seasons can be seen in Figure 3.5. The uncoppiced trees achieved a mean *height* of 148cm compared with 137cm for the trees coppiced once and 122cm for the trees coppiced twice (F Value = 23.41, $P <$ 0.0001).

Figure 3.5 The effects of coppicing on mean height in juvenile oak five growing seasons after planting.



Treatment a = uncoppiced
Treatment b = coppiced once
Treatment c = coppiced twice

Random effects, such as fertility, were responsible for differences in *height* growth. Main row effects were thus, the mean *height* of the trees in plots 4, 5, and 6 was 143cm compared with 132cm in plots 7, 8, and 9 and 135cm in plots 1, 2, and 3, (F Value = 4.22, $P < 0.0152$). Main column effects were thus, mean height in plots 3, 4, and 9 were 150cm compared with 129cm for plots 1, 2, 5, 6, 7 and 8, (F Value = 23.35, $P < 0.0001$). Plots 4 and 9 contained the tallest trees overall.

Spacing had no significant effect on *height* growth after five growing seasons but there is evidence that interactions between the coppice treatments and spacing did have an effect on *height* growth. These can be seen in Table 3.3. Mean *height* ranged from 116cm for trees that were coppiced twice at 1.0m spacing to 154cm for uncoppiced trees at 1.8m spacing, (F Value = 4.07, $P < 0.0029$).

The variables were sufficiently normally distributed to justify confidence in these results. Caution should be exercised, however, when considering data at the extremes of the frequency distribution. For example, trees that were very large when planted, compared with the generality of the population, have not responded in the same way.

An ANOVA table showing the effects of all variables on *height* five years old can be seen in Table 3.3.

Table 3.3 ANOVA of variables affecting height growth in juvenile oak after five growing seasons

Dependent Variable: *height*

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Treatment	2	60036.37	30018.18	23.41	<.0001
Spacing	2	752.12	376.06	0.29	0.7460
MR	2	10829.05	5414.52	4.22	0.0152
MC	2	59888.04	29944.02	23.35	<.0001
SR	2	3097.77	1548.88	1.21	0.2997
SC	2	5667.84	2833.92	2.21	0.1107
TR	2	48.23	24.11	0.02	0.9814
TC	2	4293.49	2146.74	1.67	0.1885
Treat*Spacing	4	20879.95	5219.98	4.07	0.0029

Treatment = coppice
MR = Main row of Latin Square
MR = Main column of Latin Square
SR = Sub-plot row
SC = Sub-plot column
TR = Tree row within sub-plots
TC = Tree column within sub-plot

3.3.2 Straightness percentage

The effect of the coppice treatments on *straightness percentage* after one growing season can be seen in Table 3.4. The mean *straightness percentage* in the coppiced trees was 98% compared with 59% in the uncoppiced trees, (F Value = 923.71, $P <$ 0001. Spacing had no significant effect on *straightness percentage*. Random effects were slightly influential. *Straightness percentage* in plots 1, 2 and 3 was 89% compared with 84% in plots 4, 5 and 6 and 85% in plots 7, 8 and 9, (F Value = 4.51, $P < 0.0013$).

Table 3.4 Juvenile oak experiment - Summary of straightness percentage 1998

Variable	Trees	Treatments	P	P <
	722	Coppice	Uncoppiced	
Straightness %		98%	59% -	0.0001

Table 3.5 shows the effects of coppicing on *straightness percentage* after two growing seasons. *Straightness percentage* in the uncoppiced trees was 69% compared with 87% in the trees coppiced once and 93% in the trees coppiced twice (F Value = 9.42, $P < 0.0002$.

Table 3.5 Juvenile oak experiment - Summary of straightness percentage 1999

Variable	Trees	Treatments		
	75	Coppice 1	Coppice 2	Uncoppiced
Straightness %		87%	93%	69%

Table 3.6 shows the effects of coppicing on *straightness percentage* after five growing seasons. Mean *straightness percentage* for the uncoppiced trees was 41% compared with 48% in the trees coppiced once and 55% in the trees coppiced twice, (F Value = 9.95, $P < 0.0001$.

Table 3.6 Juvenile oak experiment - Summary of straightness percentage 2002

Variable	Trees	Treatments		
	722	Coppice 1	Coppice 2	Uncoppiced
Straightness %		48%	55%	41%

Analysis of variance calculations can be seen in table 3.7. Some variations in straightness percentage have occurred as a result of the geographical position expressed within the main rows and sub-plot columns of the Latin square

Table 3.7 ANOVA of variables affecting straightness percentage in juvenile oak at five years old

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Treatment	2	17068.07	8534.03	10.22	<.0001
Spacing	2	3912.01	1956.00	2.34	0.0972
MR	2	7530.97	3765.48	4.51	0.0114
MC	2	2142.32	1071.16	1.28	0.2783
SR	2	3687.22	1843.61	2.21	0.1110
SC	2	5765.82	2882.91	3.45	0.0324
TR	2	610.27	305.13	0.37	0.6942
TC	2	3444.44	1722.22	2.06	0.1282
Treat*Spacing	4	492.62	123.15	0.15	0.9641

Treatment = coppice
MR = Main row of Latin Square
MR = Main column of Latin Square
SR = Sub-plot row
SC = Sub-plot column
TR = Tree row within sub-plots
TC = Tree column within sub-plot

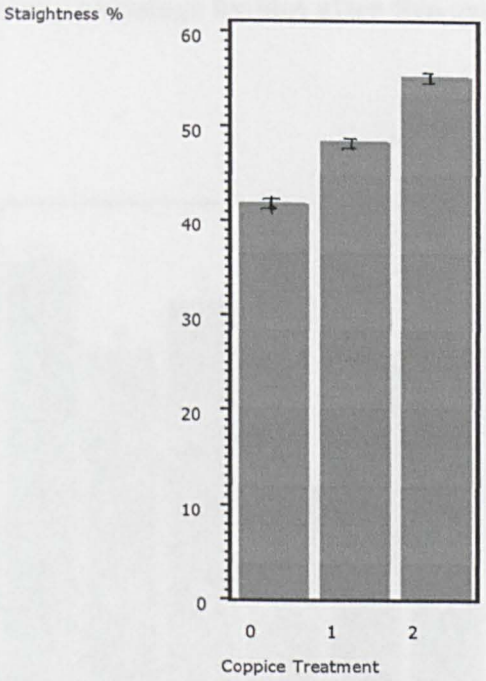
Plates 3.1 and 3.2 illustrate the typical stem form of uncoppiced and coppiced oak trees after four years growth.

Plate 3.1 Uncoppiced oak showing characteristic bent stem, long branches and bushy crown

Plate 3.2 Coppiced oak showing characteristic straight stem, short branches and narrow crown

A summary of the effects of coppicing on *straightness percentage* after five growing seasons can be seen in Figure 3.6.

Figure 3.6 The effects of coppicing, after five growing seasons, on straightness percentage in juvenile oak.



Error bars shown at ± 2 S.E.

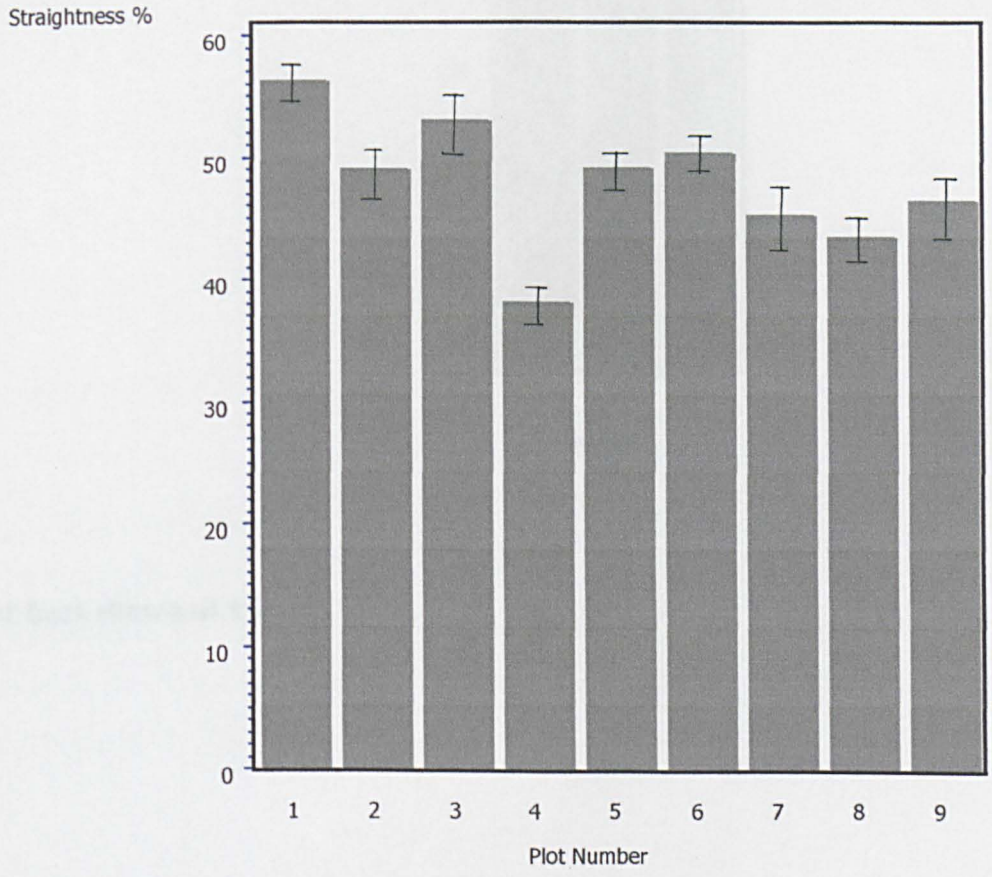
Coppice Treatment 0 = uncoppiced

1 = coppiced once

2 = coppiced twice

Significant differences were seen as a result of random site effects. These can be seen in Figures 3.7 and 3.8. *Straightness percentage* was 56% in plot 1, 49% in plot 2, 52% in plot 3, 38% in plot 4, 49% in plot 5, 50%in plot 6, 45% in plot 7, 435 in plot 8 and 46% in plot 9, (F Value = 4.51, $P < 0.0114$.

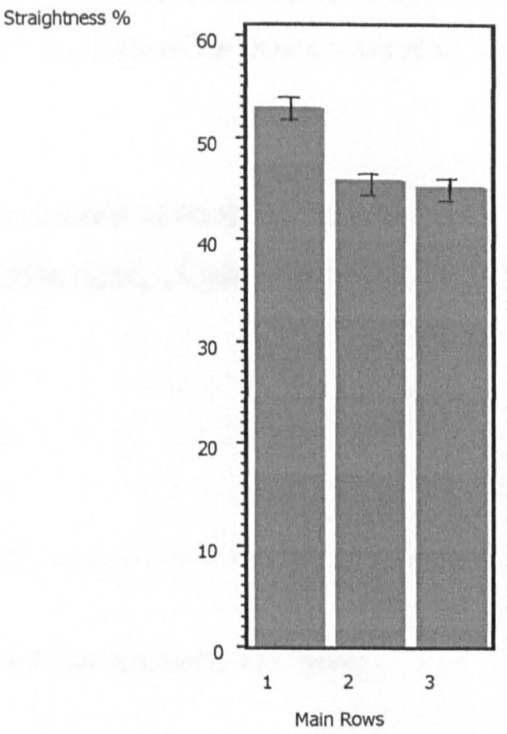
Figure 3.7 Straightness percentage by plot after five growing seasons



Error bars shown at ± 2 S.E.

Slight differences in stem straightness were also seen within individual plots. These are expressed as rows within each of the nine main plots. *Straightness percentage* in row 1 was 52% compared with 45% in row 2 and 45% in row 3, (F Value = 3.45, $P <$ 0.0324). Spacing had no effect on *straightness percentage*.

Figure 3.8 Straightness percentage by row after five growing seasons



Error bars shown at ± 2 S.E.

The distribution of *straightness percentage* varied between treatments and can be seen in Table 3.8. 40% of the uncoppiced trees had straightness percentages less than 25% compared with 27% for the trees coppiced once and 11% for the trees coppiced twice. Similarly, 14% of the uncoppiced trees had totally straight stems compared with 16% of the trees coppiced once and 20% of the trees coppiced twice.

Table 3.8 Frequency counts of straightness percentage

Straightness %	Uncoppiced	Coppiced Once	Coppiced Twice
%*	%	%	%
25<	40	27	11
50<	70	60	46
75<	81	79	76
100	14	16	20

*** Values less than 100 are not mutually exclusive**

3.3.3 Numbers of shoots

The coppice treatments had a small effect on the numbers of shoots per tree. After five growing seasons the uncoppiced trees had a mean of 1.02 stems per tree compared with 1.14 stems per tree in the trees coppiced once and 1.22 stems per tree in the trees coppiced twice, (F Value = 58.73, $P < 0.0001$).

3.4 DISCUSSION

The random effects within the experimental area were identified as interrow and intercolumn variables. These effects are independent of treatment effects. Plots 4 and 9 had the tallest trees. This is probably due to fertility gradients related to their position within the experimental area. Both plots are adjacent to mature woodland to the east and have less exposure to the north and west than any other plot. Furthermore, they are both situated in the lowest part of the area where the soil is deep and moist.

The coppice treatments were responsible for reduced height growth and better stem straightness after five growing seasons. The trees responded to the coppice treatments by sending out vigorous shoots that grew vertically. Lateral branch growth appeared to be sacrificed in favour of apical dominance. The coppiced trees were straighter and seemed to be less branchy than the uncoppiced trees. These results confirmed the preliminary findings in the sweet chestnut (Chapter Two). Spacing had no effect on either *height* or *straightness percentage*. This was to be expected because canopy closure had not yet occurred.

The experimental approach allowed for site variation by incorporating the ability to identify fertility gradients. The interrow and intercolumn grids were an effective alternative to detailed sampling and stratification of site variation but neither approach is always able to explain the relevance of underlying variation (McGarigal *et al.*, 2000).

Two particular areas of doubt remained about the validity of the work done so far. Firstly, coppicing is only one form of external trauma that can be applied to trees. Would other forms of stem damage produce growth effects similar to those caused by the coppice treatments? Secondly, the experiment was designed to take account of site variation. A series of statistical tests were carried out to determine effects. It is possible that other unknown factors were at work, which may have had important consequences on the results. For example, if the same experimental approach were carried out in ordinary woodland conditions how would underlying ecophysiological relationships between variables be identified? These questions are investigated in Chapter 4.

4. CHAPTER FOUR: FACTORS INFLUENCING VEGETATIVE REGROWTH OF DAMAGED TREE STEMS

4.1 INTRODUCTION

In chapters Two and Three I describe experiments that tested the effects of coppicing on various growth characteristics in carefully planned experimental conditions. Two questions arose. Firstly, would natural forms of damage, such as browsing, produce the same kind of growth response as that caused by the coppice treatments? Secondly, would trees grown in natural conditions, such as those experienced in a forest, respond to damage in the same way as those in the designed experiments? These questions were investigated following the second growing season of the juvenile oak experiment.

4.2 MATERIALS AND METHODS

4.21 Browsing damage in wild cherry

Investigations carried out so far were on trees that had been coppiced. It was necessary to assess the effects that other forms of damage had on tree growth. A provenance trial of seven-year-old wild cherry (*Prunus avium*) at the Riseholme Estate provided the opportunity to do this. Rabbits had completely stripped the bark from the bases of some of the trees after the second year of growth in the field. The stem and foliage above the stripped area had died back. The stems regenerated vegetatively from dormant buds below the damaged area and produced vigorous stems. Some of the stems were repeatedly damaged by rabbits over a three-year period.

4.2.2 Juvenile oak

The investigations so far had been carried out on designed experimental field trials. It was possible that the importance of the observed effects was disproportionately high because other variables, not accounted for by the experimental design, were not assessed. It was necessary to test the range of environmental influences that would normally be present in woodland conditions. Unknown factors might suppress the success of the vegetative regrowth. Further work was attempted in typical woodland conditions on the Riseholme Estate and at other estates within Lincolnshire to test the effects of a range of ecophysiological influences on the regrowth of damaged trees.

Unfortunately, it was not possible to collect enough useful data at any of these sites because of the local practice of forest management. Browsing damage was fairly common but it was never concentrated in any one area. Where such damage had occurred in the past, remedial action had been taken such as removal of the damaged trees or by pruning. In effect, evidence of browsing damage had been lost almost as soon as it had occurred.

It was still necessary to have some assessment of other possible influences on vegetative regrowth. I returned to the juvenile oak experiment, described in Chapter Three, to study these effects.

4.2.3 Measurements taken

a) Browsing damage in wild cherry

Measurements were taken in March 2000, using a one metre steel rule, of the length of stem between each annual whorl on the main stem of each tree. The timing of rabbit damage was assessed using evidence from the remains of dead shoots. Annual height growth was clearly visible.

b) Juvenile oak

A small sample of 27 trees was selected from the juvenile oak experiment. This took the form of a line of trees from the eastern edge of plot 9 to the western edge of plot 7. This line of trees was perpendicular to the mature forest edge alongside the eastern edge of the experiment. The following data were collected:

tree spacing

distance from mature forest edge

tree height

length of straight stem measured from the base of the tree

length of the longest branch on each tree

the presence of grass competition – Present/Not Present

herbaceous weeds – Present/Not Present

brambles – Present/Not Present

mosses – Present/Not Present

severity of weed competition – graded 1-5

diameter of stem at base of tree

number of stems per tree

treatment - coppiced /uncoppiced

4.2.4 Statistical analysis

a) Browsing damage in wild cherry

Differences in height were assessed using the Generalised Linear Models procedure of SAS software. See Chapters Two and Three.

b) Juvenile oak

A combination of complementary statistical techniques was used. This was carried out in the following stages.

Principal Component Analysis (PCA) was used to produce a correlation matrix of factors. This was used as an exploratory procedure.

Eigenvalues of the correlation matrix were then listed to determine the importance of the principal components. This was carried out using the MINEIGEN procedure in SAS. This is based on the *Latent Root Criterion* approach or Kaiser-Guttman criterion (Guttman, 1954; Cliff, 1988). In essence, components with eigenvalues less than one are not investigated further.

Eigenvectors of the correlation matrix were then produced for the retained components. These were converted into principal component loadings to offset the distorting effects of the original measurement scales of the variables. The resulting principal components in the component structure are referred to as Factors.

The analysis of the principal component loadings was carried out using the following guidelines:

Principal component loadings greater than 0.32 or less than -0.32 - poor
Principal component loadings greater than 0.45 or less than -0.45 – fair
Principal component loadings greater than 0.55 or less than -0.55 - good
Principal component loadings greater than 0.63 or less than -0.63 – very good
Principal component loadings greater than 0.71 or less than -0.71 – excellent

(Tabachnik and Fidell, 1989)

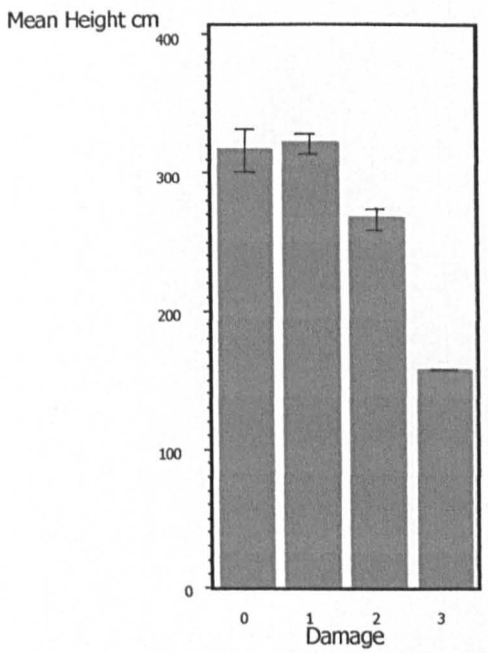
The principal component axes were then rotated about the centroid to simplify and improve the component interpretation. This was achieved using the varimax rotation in SAS software.

4.3 RESULTS

4.3.1 Browsing damage in wild cherry

Height differences in wild cherry can be seen in Figure 4.1. Measurements were taken from growing seasons 1995 to 1999. One tree was undamaged, rabbits damaged 32 trees in 1995, ten trees were damaged in 1996, 19 were damaged in 1997, 30 were damaged in 1998 and 10 in 1999. Damage was defined as the tree being completely girdled by rabbits so that everything above ground was killed.

Figure 4.1 Height differences in wild cherry



Key
Damage = 0 Not browsed
Damage = 1 Browsed in 1995
Damage = 2 Browsed in 1995 + 1996
Damage = 3 Browsed in 1995, 1996 + 1997
Error bars shown at ± 2 S.E.
Only 1 observation for Damage = 3

At the end of 1999 the mean height of the undamaged trees was 317cm compared with 322cm for the trees damaged in 1995. This was not significant. On the other hand, the mean height of the trees that were damaged for three years in succession was 228cm compared with 268cm for the trees damaged two years in succession and 317cm for the undamaged trees, (F Value = 8.43, $P < 0061$). Apart from the one tree

that was damaged three years in succession there was very little difference in *height* between the damaged and undamaged trees. The trees in this study tolerated rabbit damage for at least two years in succession without any appreciable difference in *height* growth.

4.3.2 Juvenile oak

Table 4.1 shows the truncated correlation matrix of all the variables. Significant correlations exist between basal diameter and height, longest branch and height, straight length and height, location and moss, basal diameter and longest branch, number of stems and basal diameter, basal diameter and coppice treatment.

Table 4.1 Correlation matrix of environmental variables in juvenile oak

Correlation Matrix

	location	height	sl	lb	herbs	brambles
spacing	0.1635	-.1539	-.0763	-.1180	0.4001	-.2413
location	1.0000	-.0888	0.2129	-.2405	0.4413	0.2215
height	-.0888	1.0000	0.5508	0.7739	0.0147	-.0855
sl	0.2129	0.5508	1.0000	0.1378	0.0321	-.0705
lb	-.2405	0.7739	0.1378	1.0000	0.1506	-.0767
herbs	0.4413	0.0147	0.0321	0.1506	1.0000	-.1474
brambles	0.2215	-.0855	-.0705	-.0767	-.1474	1.0000
moss	0.7553	0.0576	0.2802	-.0426	0.0598	0.4670
weedcomp	0.1540	-.2833	-.2460	-.0136	0.3812	0.1574
bd	-.1412	0.5762	0.3154	0.5882	0.1679	-.0993
stem	0.2349	-.0127	0.0688	0.0356	0.2887	0.1277
treat	0.0642	0.0147	0.1943	0.0959	0.0000	-.1474
sp	0.3330	-.1709	0.6712	-.4370	0.0963	0.0511

Truncated

Key

spacing	Tree Spacing,	location	Distance From Mature Forest Edge,
height	*height,*	sl	*straight length,*
lb	*longest branch,*	herbs	Herbaceous Weeds,
brambles	Brambles,	moss	Mosses,
weedcomp	Severity of Weed Competition - Graded 1-5,		
bd	Diameter of Stem at Base of Tree,		
stem	Number of Stems Per Tree,		
treat	Treatment - coppiced (b) v Uncoppiced (u),		
sp	*straightness percentage*		

The eigenvalues of the correlation matrix are shown in Table 4.2. Using the Kaiser-Guttman Criterion, only the first five eigenvalues are greater than one.

Table 4.2 Eigenvalues of the Correlation Matrix in juvenile oak

	Eigenvalue	Difference	Proportion	Cumulative	
1	3.00332107	0.51660847	0.2310	0.2310	
2	2.48671260	0.54784673	0.1913	0.4223	
3	1.93886587	0.41450310	0.1491	0.5715	
4	1.52436277	0.05500781	0.1173	0.6887	
5	1.46935497	0.65076343	0.1130	0.8017	
>>>>

The component structure was assessed systematically by using procedures recommended by (McGarigal *et al.*, 2000). The highest loading for each variable across each factor was identified. Thus, for example, it can be seen that the highest loadings for location, lb and bd have been located and marked with an asterisk in Factor 1 in Table 4.4.

Table 4.4 Principal component structure in juvenile oak - Factor 1

Factor Pattern

		Factor1	
spacing	Tree Spacing	0.34865	
location	Distance From Mature Forest Edge	0.63363	*
height	*height*	-0.62044	
sl	*straight length*	-0.04544	
lb	*longest branch*	-0.63815	*
herbs	Herbaceous Weeds	0.26637	
brambles	Brambles	0.26176	
moss	Mosses	0.48638	
weedcomp	Severity of Weed Competition - Graded 1-5	0.43067	
bd	Diameter of Stem at Base of Tree	-0.72044	*
stem	Number of Stems Per Tree	0.48272	
treat	Treatment - coppiced (b) v Uncoppiced (u)	0.34881	
sp	*straightness percentage*	0.50080	

The factor pattern in Table 4.4 shows that increases in basal diameter are related to increases in *height,* and *longest branch.* This would seem to be correct because, intuitively, as trees increase in size, the individual parts of a tree, such as branch length and tree height are proportional

As the distance from the mature forest edge increases, basal diameter, *height* and *longest branch* decreases. There is a negative gradient between the distance from the forest edge and overall tree size. This would indicate the existence of a forest edge effect.

Straight length is not related to location or to overall tree size as described by such variables as *height, longest branch* and basal diameter.

As would be expected, location is also related to such things as tree spacing, concentrations of mosses and also the severity of weed competition. The coppice treatments are also related to location.

Decreases in *longest branch* are associated with reductions in tree spacing, increased weed competition, concentrations of mosses, increases in stem numbers and improvements in *straightness percentage*.

As basal diameter decreases, *straightness percentage* increases. *Straightness percentage* and the coppice treatments are related to one another and both are negatively related to basal diameter. This is probably due to the initial small basal diameter of the coppice regrowth compared with the established stems of the uncoppiced trees.

Factor 1 confirms the proportionality between some of the main individual morphological characteristics of the trees in the study and relates these to their geographical position within the experimental area.

Table 4.5 Principal component structure in juvenile oak - Factor 2

Factor Pattern

		Factor2	
spacing	Tree Spacing	-0.21030	
location	Distance From Mature Forest Edge	0.48383	
height	*height*	0.65940	*
sl	*straight length*	0.81931	*
lb	*longest branch*	0.40601	
herbs	Herbaceous Weeds	0.23402	
brambles	Brambles	0.14603	
moss	Mosses	0.61599	*
weedcomp	Severity of Weed Competition - Graded 1-5	-0.19372	
bd	Diameter of Stem at Base of Tree	0.37256	
stem	Number of Stems Per Tree	0.26861	
treat	Treatment - coppiced (b) v Uncoppiced (u)	0.24866	
sp	*straightness percentage*	0.41427	

The principal component structure of Factor 2 can be seen in Table 4.5. The predominant variable is *straight length.*

As *straight length* increases, *height* increases. *Straight length* is also associated with mossy areas. *Straight length* increases with location, longest branch, basal diameter and *straightness percentage.*

Height is related to location, *longest branch*, mosses, and *straightness percentage.* Apart from moss, these relationships reflect the proportionality evident between the morphological characteristics in trees seen in Factor 1.

The existence of mosses as a major vegetation type is related to improvements in growth performance as defined *by height, longest branch, straightness percentage, straight length,* and basal diameter. Mosses probably represent a lack of weed competition for tree growth. In this context ground vegetation that is predominantly moss provides a weed free environment for the trees to grow.

Moss is also related to the distance from the mature forest edge. Further investigations did nothing to clarify this. It was probable that the predominance of moss far from the forest edge was coincidental and probably due to factors not accounted for by the study. The most likely explanation is variation in moisture content and retention in the soil.

The study area was not weeded for two years prior to measurement. Factor 2 illustrates the relationship between tree growth in areas with and without moss. An examination of the site after the formal assessments were taken indicated that where mosses predominated other weed types suffered.

Table 4.6 Principal component structure in juvenile oak - Factor 3

Factor Pattern

		Factor3	
spacing	Tree Spacing	0.70722	*
location	Distance From Mature Forest Edge	0.04894	
height	*height*	0.17804	
sl	*straight length*	-0.06713	
lb	*longest branch*	0.39658	
herbs	Herbaceous Weeds	0.74618	*
brambles	Brambles	-0.41043	
moss	Mosses	-0.33540	
weedcomp	Severity of Weed Competition - Graded 1-5	0.53462	*
bd	Diameter of Stem at Base of Tree	0.19973	
stem	Number of Stems Per Tree	0.24482	
treat	Treatment - coppiced (b) v Uncoppiced (u)	0.04616	
sp	*straightness percentage*	-0.13165	

The principal component structure of Factor 3 can be seen in Table 4.6. The predominant variables are herbaceous weeds, tree spacing and the severity of weed competition. Herbaceous weeds and weed competition are related to tree spacing. Wider tree spacings provide less competition for sunlight, moisture and nutrients. Herbaceous weeds are negatively related to mosses.

Herbaceous weeds and the extent of weed competition may also be related to increases in *longest branch.* As tree spacings get wider *longest branch* increases. Brambles are negatively related to tree spacing.

Factor 3 is primarily focussed on relationships between weeds and tree spacing.

Table 4.7 Principal component structure in juvenile oak - Factor 4

Factor Pattern

		Factor4	
spacing	Tree Spacing	-0.20016	
location	Distance From Mature Forest Edge	0.27973	
height	*height*	0.03004	
sl	*straight length*	-0.47649	
lb	*longest branch*	0.28866	
herbs	Herbaceous Weeds	0.17197	
brambles	Brambles	0.64133	*
moss	Mosses	0.39962	
weedcomp	Severity of Weed Competition - Graded 1-5	0.29291	
bd	Diameter of Stem at Base of Tree	0.12835	
stem	Number of Stems Per Tree	0.02614	
treat	Treatment - coppiced (b) v Uncoppiced (u)	-0.31696	
sp	*straightness percentage*	-0.53925	*

The principal component structure of Factor 4 can be seen in Table 4.7. The predominant variables are brambles and *straightness percentage.* Brambles are negatively related to *straightness percentage* and *straight length*. An on site inspection of this phenomenon revealed that brambles had spread outwards and over the top of some trees. The leading shoots and stems of the affected trees were often bent over from the weight of the brambles. When the brambles were cleared, not all of the trees assumed their natural open grown state.

Brambles are negatively related to the coppice treatments. Brambles seem to be slightly shade tolerant. (In Factor 4, Table 4.6, brambles were negatively related to tree spacing).

Table 4.8 Principal component structure in juvenile oak - Factor 5

Factor Pattern

		Factor5	
spacing	Tree Spacing	-0.15237	
location	Distance From Mature Forest Edge	-0.28403	
height	*height*	0.16002	
sl	*straight length*	-0.17927	
lb	*longest branch*	0.35274	
herbs	Herbaceous Weeds	-0.21601	
brambles	Brambles	-0.05720	
moss	Mosses	0.05457	
weedcomp	Severity of Weed Competition - Graded 1-5	-0.05856	
bd	Diameter of Stem at Base of Tree	-0.41108	
stem	Number of Stems Per Tree	0.52147	*
treat	Treatment - coppiced (b) v Uncoppiced (u)	0.74063	*
sp	straightness percentage	-0.37081	

The principal component structure of Factor 5 can be seen in Table 4.8. The predominant variables are the number of stems per tree and coppice treatments. The number of stems per tree increases with coppice treatments.

Table 4.9 Rotation of component structure in juvenile oak – Factor 1

Rotation Method: Varimax

Rotated Factor Pattern

		Factor1
spacing	Tree Spacing	-0.09573
location	Distance From Mature Forest Edge	-0.13210
height	*Height*	0.94681*
sl	*Straight length*	0.38546
lb	*Longest Branch*	0.92450*
herbs	Herbaceous Weeds	0.08252
brambles	Brambles	-0.04822
moss	Mosses	0.03973
weedcomp	Severity of Weed Competition - Graded 1-5	-0.09848
bd	Diameter of Stem at Base of Tree	0.60401*
stem	Number of Stems Per Tree	-0.00301
treat	Treatment - coppiced (b) v Uncoppiced (u)	0.02562
sp	*straightness percentage*	-0.29057

The rotated component structure of Factor 1 can be seen in Table 4.9. The predominant variables are *height, length of the longest branch* and basal diameter. These variables are strongly related to each other. *Straight length* is also related to these predominant variables.

Factor 1 reflects the proportionality of morphological characteristics in trees.

Table 4.10 Rotation of component structure in juvenile oak – Factor 2

Rotation Method: Varimax

Rotated Factor Pattern

		Factor2
spacing	Tree Spacing	-0.04567
location	Distance From Mature Forest Edge	0.90701*
height	*Height*	0.02168
sl	*Straight Length*	0.16131
lb	*Longest Branch*	-0.09840
herbs	Herbaceous Weeds	0.17606
brambles	Brambles	0.22025
moss	Mosses	0.88227*
weedcomp	Severity of Weed Competition - Graded 1-5	0.03664
bd	Diameter of Stem at Base of Tree	-0.12016
stem	Number of Stems Per Tree	0.12604
treat	Treatment - coppiced (b) v Uncoppiced (u)	0.07604
sp	*straightness percentage*	0.13618

The rotated component structure of Factor 2 can be seen in Table 4.10. The predominant variables are location and mosses. Factor 2 shows that mosses are highly related to the distance from the forest edge.

Table 4.11 Rotation of component structure in juvenile oak – Factor 3

Rotation Method: Varimax

Rotated Factor Pattern

		Factor3
spacing	Tree Spacing	0.03238
location	Distance From Mature Forest Edge	0.15440
height	*Height*	0.14726
sl	*Straight Length*	0.86412*
lb	*Longest Branch*	-0.20386
herbs	Herbaceous Weeds	0.02580
brambles	Brambles	-0.01542
moss	Mosses	0.14346
weedcomp	Severity of Weed Competition - Graded 1-5	-0.06127
bd	Diameter of Stem at Base of Tree	0.13003
stem	Number of Stems Per Tree	0.05215
treat	Treatment - coppiced (b) v Uncoppiced (u)	0.11418
sp	*straightness percentage*	0.92534*

The rotated component structure of Factor 3 can be seen in Table 4.11. The predominant variables are straight length and straightness percentage. Factor 3 confirms the obvious relationship between these two variables.

Table 4.12 Rotation of component structure in juvenile oak – Factor 4

Rotation Method: Varimax

Rotated Factor Pattern

		Factor4
spacing	Tree Spacing	-0.01590
location	Distance From Mature Forest Edge	-0.01618
height	*Height*	-0.02936
sl	*Straight Length*	0.07750
lb	*Longest Branch*	0.10194
herbs	Herbaceous Weeds	-0.03938
brambles	Brambles	-0.09806
moss	Mosses	0.14903
weedcomp	Severity of Weed Competition - Graded 1-5	0.05490
bd	Diameter of Stem at Base of Tree	-0.41710
stem	Number of Stems Per Tree	0.23420
treat	Treatment - coppiced (b) v Uncoppiced (u)	0.95788*
sp	*straightness percentage*	0.06336

The rotated component structure of Factor 4 can be seen in Table 4.12. There is a negative relationship between the coppice treatments and basal diameter.

4.4 DISCUSSION

Height differences in wild cherry

No differences in *height* were observed in wild cherry that had been browsed in one growing season compared with undamaged trees. The *height* of trees browsed in successive years was adversely slightly affected as a result of the rabbit damage. This follows the results found for the coppice treatments found in the sweet chestnut studied in Chapter Two and the oak in Chapter Three. Leffelman and Hawley (1925) noted that the method of cutting did not have any effect on the success rate of regrowth of new shoots when the original stems were less than 5cm diameter. In these experiments it did not matter whether the original stems were cut by clearing saw or girdled by rabbits, the resulting regrowth was equally successful.

Principal component analysis

The principal component analysis revealed that, in Factor 1, the morphological characteristics of the trees in the study were proportional to one another. Positive relationships existed between *height* and basal diameter, *height* and *longest branch*, *height* and *straight length*, basal diameter and *longest branch*. An inverse relationship existed between *straightness percentage* and *longest branch*.

Interestingly, in the context of the experimental approach, the relationship between mosses and location demonstrated which site variables were entitled to be regarded as deserving of further investigation. Information was gained about the relationships between the various weed types. Herbaceous weeds were not found where mosses were dominant, for example. Aspects of weed growth became apparent only as a result of the principal component analysis. The negative effect of brambles on *straightness percentage* had not been expected, neither was the relationship between spacing and brambles.

This was a pilot study: only 27 trees were used. The general aim had been to test the effectiveness of the statistical approach used in Chapters Two and Three. The analysis of variance procedures used in these chapters produced an effective method of hypothesis testing but were only able to detect a two dimensional view of the experimental area. The *a priori* objectives and conceptions of the researcher

determined this view. The principal component analysis took a multi dimensional view of the experimental area that was not constrained by the specific *a priori* objectives of the researcher. It was capable of recognising site gradients and relationships that were both independent and dependent of the variables chosen for hypothesis testing. It provided a means of screening out unnecessary noise and separating positive relationships from inverse relationships so that the subsequent hypothesis testing could be properly focussed. Without the knowledge provided by the principal component analysis the effect of positive and negative relationships within the data sets could confuse the application of analysis of variance procedures. In these studies, for example, the strong positive relationship between *height* and *longest branch* had to be separated from the effects of the negative relationship between *straightness percentage* and *longest branch* before relevant analysis of variance procedures could be carried out.

Principal component analysis produced an overview of biological processes that was independent of experimental objectives. It also contextualised these objectives. It added a level of rigour to the scientific process more akin to philosophy, that of scepticism. I was forced express this scepticism in a form of self-examination of my experimental objectives.

The principal component analysis revealed hidden relationships in the data that may not have been detected by intuition. In Chapter Five I extend this technique to explore possible relationships between morphological traits in a range of species and age classes.

5. CHAPTER FIVE: RELATIONSHIPS BETWEEN STEM FORM AND BRANCH LENGTH IN SOME BROADLEAVED TREE SPECIES

5.1 INTRODUCTION

In Chapter Three I investigated the effects of coppicing on various morphological characteristics of juvenile oak trees. Coppicing improved stem straightness. The coppiced trees had smaller branches than the uncoppiced trees. It seemed as though the coppiced trees had sacrificed branchiness in favour of apical dominance. Coppicing had a causal effect on *straightness percentage* and *longest branch.*

In Chapter Four I investigated an analytical approach that was based on principal component analysis. This was found to be effective in identifying on site variation that could be expressed as experimental variables. These procedures revealed both positive and negative relationships between morphological characteristics. To what extent can these relationships be used to describe how trees develop?

This chapter presents an assessment of the relatedness of three characteristics, *longest branch, height* and stem straightness, in a range of species and age classes.

Stem straightness is usually regarded as an essential feature of good quality in timber trees. A range of methods has been devised to assess straightness. Barnes & Gibson (1986) found that the simpler methods were sometimes inconsistent while the more complex methods were often too costly. These range from simple subjective scales (Barrett & Mullin, 1968) to quantitative methods that are related to utilisation (Barnes & Gibson, 1986). Begbie (1999) balanced the cost of assessment of morphological traits with the economic importance of those traits. Cundall *et al.* (1998) describe stem form in young trees by using subjective scales of straightness with quantitative assessments of branch architecture. These techniques produce descriptions of tree form that can be used by forest geneticists and foresters but they do little to explain possible predictive relationships between various morphological factors.

The typical decurrent crown form of large open-grown oaks is a result of weak apical

dominance of terminal buds over lateral buds (Brown *et al.*, 1967). Crops grown at high density grow taller and with fewer large branches (Harmer, 1989). The control of lateral bud activity, the development of side branches and the extent of apical dominance can be altered by manipulating crop density. Crops grown at high densities also produce trees with straighter stems (Savill & Spilsbury, 1991; Kerr & Evans, 1993). High stocking densities usually discourage epicormic development in young oaks and induce apical dominance. The potential for the production of veneer butts is increased due to fewer and smaller knots.

5.2 MATERIALS AND METHODS

Data were collected from various tree species, most of which were pedunculate oak, sweet chestnut, ash and sycamore, at the Riseholme and Yarborough Estates in Lincolnshire and at the Mulgrave Estate in Yorkshire. The oak plots were established in 1997, using two-year old containerised plants produced from locally collected acorns. The sweet chestnut plot was planted in 1992 as part of a provenance trial. The sycamore was established as a shelterbelt in 1995. Measurements were carried out between November 1999 and March 2000. The Ash formed part of a seedling orchard established in 1993 at the Mulgrave Estate. Measurements were taken in November 2001. Mature specimens of various species were also measured on parkland at the Riseholme Estate. Semi mature ash and sycamore were measured at Yarborough in January 2002.

5.2.1 Measurements taken

a) Height

Height was assessed by measuring the height of the tree from ground level or root collar, whichever is higher, to the top of the leading shoot or bud (Hamilton, 1975).

b) Straight length

Straight length is described as the length of straight stem, to the point where the main stem becomes indistinguishable or springs into the crown. A stem is considered straight until a bend or kink causes an angular deviation. Slight bowing is acceptable.

c) Longest Branch

For reasons of economy and practicality I decided to minimise the number of measurements of branches on any one tree. Measurements of every branch include assessments of sub-branches. Each individual measurement is prone to error because decisions have to be made, in each case, where to measure from and where to measure to. As branches become smaller these decisions become more subjective.

It was essential to limit the number of observations to the most influential branches. I assumed that if branch length were related to stem straightness then all branches

would probably have an influence but it was likely that long branches would have more influence than smaller branches. Long branches exert more leverage on the stem than short branches and they usually have larger diameters at the axil. It was logical to measure the length of the *longest branch* on each tree because such a branch would probably be more influential than lesser branches. This novel approach could always be abandoned if it proved to be irrelevant. *Longest branch* is defined as the length of the *longest branch* of a tree measured from the axil to the tip of the branch.

5.2.2 Exploratory methods and analysis

A series of exploratory procedures were undertaken to analyse the data. These were intended to identify possible relationships between individual morphological characteristics.

a) Size related differences

It was likely that at some, though not all, morphological characteristics were proportional to others. It is well known that not all characteristics are proportional. Large trees do not have larger leaves than small trees. Similarly, bud size is not dependent on the size of the tree. The relevant questions in this study were:

- Would taller trees have proportionally longer branches than shorter trees? This was achieved by comparing *height* with *longest branch.*
- Would taller trees have longer *straight lengths* than shorter trees? Possible size related differences were removed by converting straight stem length to *straightness percentage.*

Thus *straightness percentage* = (*straight length* ÷ *height*)*100.

b) Relationship between longest branch, straight length and height

Two exploratory methods were used to explore and describe relationships between *longest branch, straight length* and *height.*

- *Branch factor*, defined as *branch factor* = *longest branch* ÷ *straight length.*
- *Ratio,* defined as *ratio* = *height* ÷ *longest branch.*

5.2.3 Statistical analysis

Principal component analysis was used to explore relationships between variables. Regression analysis was used to analyse the gradients identified in the principal component analysis. Regression analysis was also used to explore relationships between *branch factor/straightness percentage* and *ratio/straightness percentage*.

5.3 RESULTS

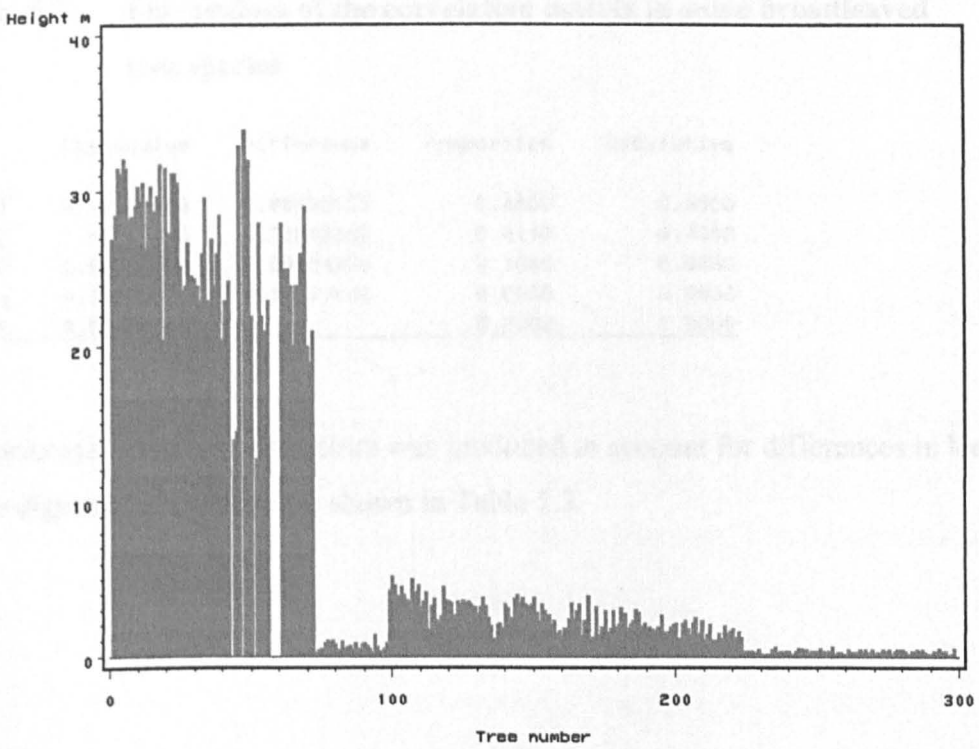
Descriptive statistics of the trees in this chapter can be seen in Table 5.1. Age classes at Riseholme arboretum are estimated.

Table 5.1 Descriptive statistics of trees studied in Chapter Five

Species	Location	Number	Age in years
sweet chestnut	Riseholme	469	7
oak	Riseholme	81	3
sycamore	Riseholme	26	4
ash	Mulgrave	126	7
ash	Yarborough	27	62-63
sycamore	Yarborough	15	62-63
oak	Riseholme arboretum	4	>200
beech	Riseholme arboretum	14	60 –250
sycamore	Riseholme arboretum	5	60 –100
rowan	Riseholme arboretum	1	-
walnut	Riseholme arboretum	1	-
horse chestnut	Riseholme arboretum	1	>200
lime	Riseholme arboretum	4	>200
All	-	774	-

The distribution of the tree *heights* encountered in the study is illustrated in Figure 5.1. There are very few trees between five and 18 metres in height. It was not possible to find many suitable trees in the missing *height* classes because those that were available tended to occur in unthinnned stands where branch competition was severe.

Figure 5.1 Distribution of tree heights



Principal component analysis

Eigenvalues can be seen in Table 5.2. Using the *Latent Root Criterion* approach, components with eigenvalues less than one are not investigated further. The first two eigenvalues are therefore used in the analysis.

Table 5.2 Eigenvalues of the correlation matrix in some broadleaved tree species

	Eigenvalue	Difference	Proportion	Cumulative
1	2.42505958	0.86839165	0.4850	0.4850
2	1.55666793	0.71342332	0.3113	0.7963
3	0.84324461	0.69934234	0.1686	0.9650
4	0.14390227	0.11277665	0.0288	0.9938
5	0.03112561		0.0062	1.0000

The principal component structure was produced to account for differences in loading of the eigenvectors. These are shown in Table 5.3.

Table 5.3 Principal component structure in some broadleaved tree species

Factor Pattern

	Factor1	Factor2	Factor3	Factor4	Factor5
H	0.68763	0.68871*	-0.16858	-0.11245	0.10858
SL	-0.34355	0.93041*	0.00415	-0.07137	-0.10583
LB	0.91981*	0.16184	-0.23343	0.26619	-0.04904
age	0.48308	0.12517	0.86627*	0.02332	-0.00027
sp	-0.86878*	0.41812	0.09947	0.23401	0.07571

Variance Explained by Each Factor

Factor1	Factor2	Factor3	Factor4	Factor5
2.4250596	1.5566679	0.8432446	0.1439023	0.0311256

Highest component loadings between each factor are shown with an asterix. There is a very strong negative relationship between *longest branch* and *straightness percentage*. As *longest branch* increases *straightness percentage* decreases. There is also a negative relationship between *straightness percentage* and *height* and between *straightness percentage* and age. *Straightness percentage* declines in taller and older trees.

As would be expected, *longest branch* is strongly related to *height* and also related to age. Tall trees have proportionately longer branches than short trees. As would be expected *straight length* is related to *straightness percentage*.

The main emphasis is Factor 1 is the negative relationship between *longest branch* and *straightness percentage.*

The main feature in Factor 2 is a strong relationship between *straight length* and *height.* There is also a relationship between *height* and *straightness percentage.* This apparently contradicts the loadings in Factor 1. To seek further clarification, the loadings were rotated using the varimax rotation procedure in SAS. The results of this can be seen in Table 5.4.

Table 5.4 Rotation of component structure in some broadleaved tree species

Rotation Method: Varimax

Rotated Factor Pattern

	Factor1	Factor2	Factor3	Factor4	Factor5
H	0.91371*	0.26339	0.15030	-0.14137	0.23064
SL	0.12698	0.98644*	-0.01251	-0.07954	0.06582
LB	0.93159*	-0.28705	0.12103	0.01961	-0.18632
age	0.14410	-0.05644	0.98766*	-0.02355	0.00488
sp	-0.50681	0.76738*	-0.15263	0.35953	-0.04154

Variance Explained by Each Factor

Factor1	Factor2	Factor3	Factor4	Factor5
1.9964541	1.7168826	1.0361611	0.1565130	0.0939893

Highest component loadings between each factor are shown with an asterix. In Factor 1 there is a very strong relationship between *longest branch* and *height. Straightness percentage* is negatively related to *height* and negatively related to *longest branch.* Factor 1 one reflects the proportionality between *height* and *longest branch* and the gradient between these variables and *straightness percentage.*

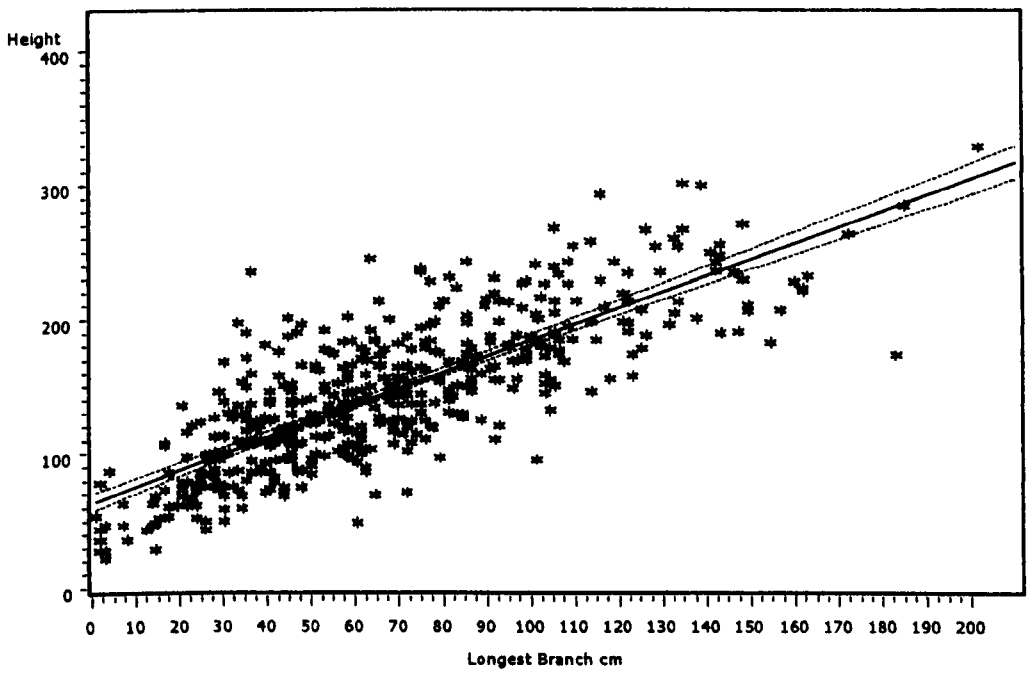
Factor 2 reflects the obvious relationship between *straight length* and *straightness percentage.*

Evidence from the principal component analysis suggests that morphological characteristics such as *height* and *longest branch* are strongly related. There is also a negative relationship between *straightness percentage* and *longest branch.* These aspects are studied in more detail in the remainder of the chapter.

5.3.1 Relationships between height and longest branch

A graphical representation of the relationship between *height* and *longest branch* in sweet chestnut for can be seen in Figure 5.2.

Figure 5.2 Relationship between height and longest branch in juvenile sweet chestnut



$R^2 = 0.62$ $P < 0.0001$ F Stat = 774.75

Model Equation - *height* = 84.1916 – 0.5211 * *longest branch*

Mean confidence limits shown at 95%

The relationship between *height* and *longest branch* in sweet chestnut confirms the proportionality of these variables seen in the principal component analysis. The sweet chestnut studied here were seven years old when measured. Relationships between *height* and *longest branch* for all species, age classes and sites can be seen in Table 5.5.

Table 5.5 Best fit relationships between height and longest branch

Species	R^2	P<	F Stat	Model Equation
sweet chestnut	0.62	0.0001	774.75	Linear
3 year old oak	0.33	0.0001	35.69	Linear
4 year old sycamore	0.57	0.0001	31.45	Linear
7 year old ash	0.71	0.0001	291.98	Linear
Yarborough ash & sycamore	0.23	0.0013	12.00	Linear
Riseholme arboretum	0.53	0.0001	31.72	Linear
All	0.93	0.0001	3113.77	Cubic

Where h = *height* and lb = *longest branch*

Increases in *longest branch* were related to increases in *height.* As would be predicted, as trees grow taller, branches grow proportionately longer. The sweet chestnut and seven-year-old ash have strong relationships between *height* and *longest branch.* The older ash and sycamore at Yarborough estate and the three year old oak have less strong relationships.

The young trees had been able to grow freely without any restriction on branch growth. The mature trees at Yarborough were part of a dense forest canopy and had been competing for light for many years. They had been growing in forest conditions and undergoing regular silvicultural treatments such as thinnings for many decades. Branches had never been allowed to develop freely. The older trees at Riseholme arboretum had fairly strong relationships between *height* and *longest branch.* As arboretum trees, they have a history of growing out in the open with few constraints on branch development. The relationship between *height* and *longest branch* in these trees followed the pattern of the younger trees. The oak had undergone coppice treatments as described in Chapter Three. Normal branch development had been interfered with.

5.3.2 Best fit relationships between straightness percentage and longest branch

Height, straight length, and *longest branch* data were normally distributed. *Straight length* data were converted to *straightness percentage* to take account of possible *height* related differences. Relationships between *straightness percentage* and *longest branch* are shown in Table 5.6.

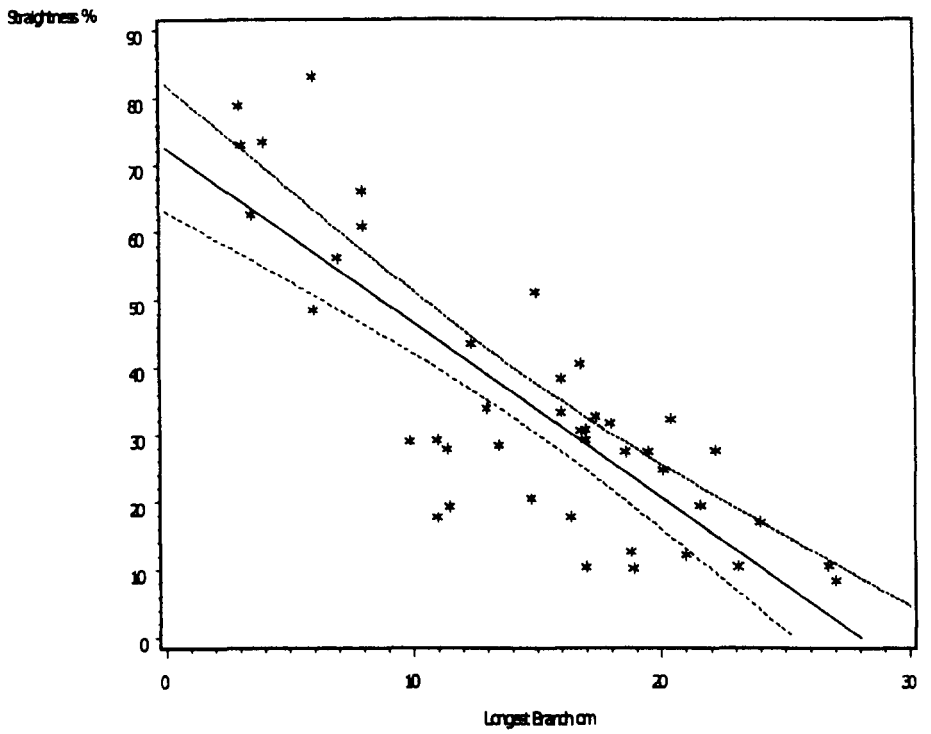
Table 5.6 Relationships between straightness percentage and longest branch

Species	R^2	P<	F Stat	Model Equation
sweet chestnut	0.30	0.0001	103.95	Quadratic
3 year old oak	0.60	0.0001	105.56	Linear
4 year old sycamore	0.71	0.0001	17.29	Cubic
7 year old ash	0.49	0.0001	112.63	Linear
Yarborough ash & sycamore	0.67	0.0001	79.22	Linear
Riseholme arboretum	0.48	0.0001	8.06	Cubic
All	0.19	0.0001	58.66	Cubic

Where sp = *straightness percentage* and lb = *longest branch*

Significant relationships exist in all populations of trees in the study but R^2 values are quite low. In the juvenile sweet chestnut, for example, 70% of the variance remains unexplained. The best fit is in the mature ash and sycamore growing in forest conditions at Yarborough Estate. Only 33% of the variance remains unexplained. This relationship can be seen in Figure 5.3.

Figure 5.3 Relationship between straightness percentage and longest branch in mature ash and sycamore from Yarborough Estate



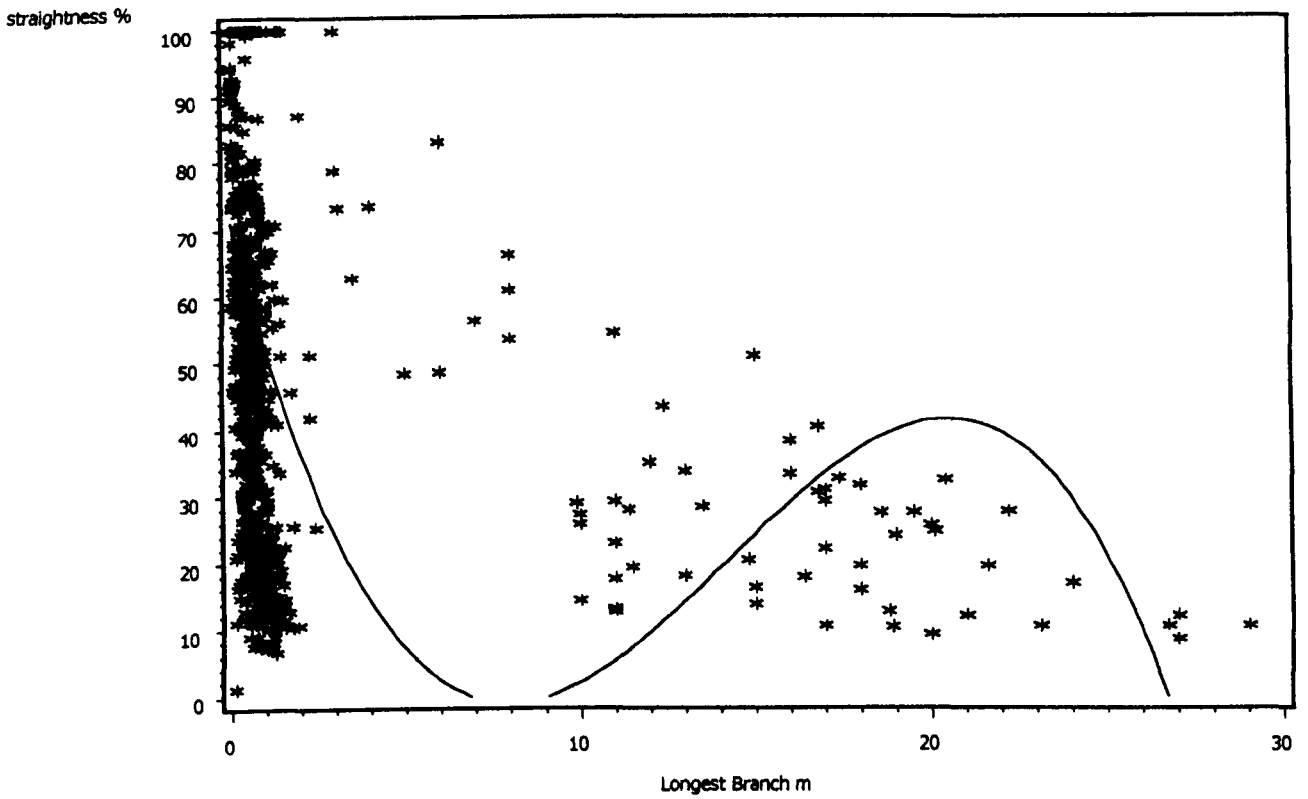
$R^2 = 0.67$, F Stat = 79.22, $P < 0.0001$

Mean confidence limits shown at 95%

Straightness percentage is negatively related to *longest branch* in the trees at Yarborough estate. 469 sweet chestnut trees were measured compared with only 42 mature trees at Yarborough. None of the trees at Yarborough have totally straight stems (where *straightness percentage* =100) compared with 297 of the sweet chestnut trees.

When all of the populations of trees are analysed together, $R^2 = 0.19$. Figure 5.4 illustrates this extremely weak relationship.

Figure 5.4 Cubic relationship between straightness percentage and longest branch in all trees



$R^2 = 0.19$ F Stat = 58.66 $P < 0.0001$

Mean confidence limits shown at 95%

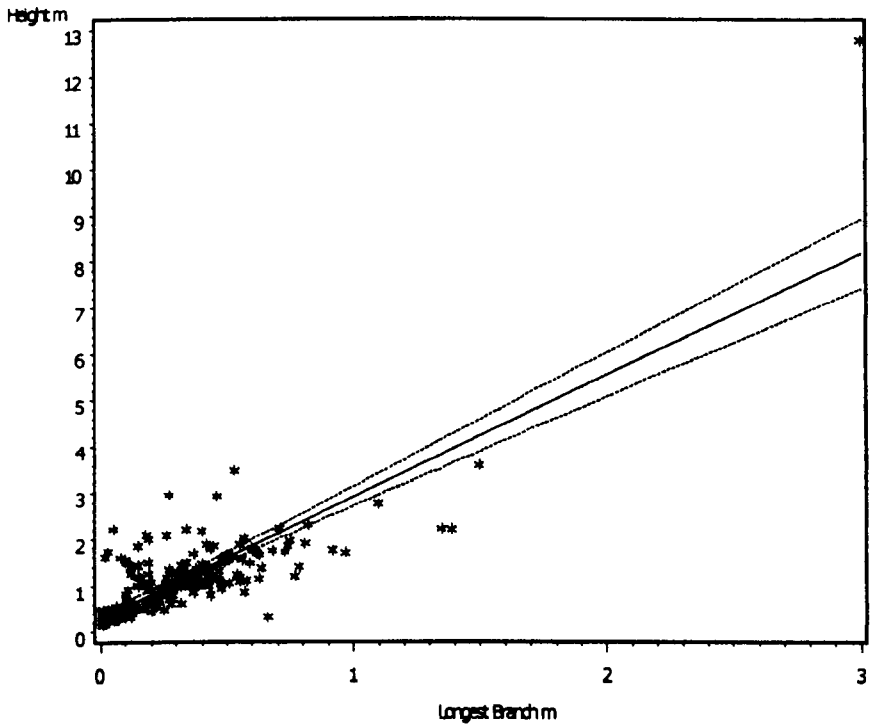
There are, quite clearly, two separate data swarms in Figure 5.4. The vertical swarm is characterised by *longest branches* less than 2m in length. The vast majority of trees with totally straight stems also lie within this swarm. These are the juvenile oak, ash, sycamore and sweet chestnut. The second swarm is characterised by having *longest branches* greater than 2m. These are the older specimens at Riseholme and Yarborough.

It cannot be concluded, however that older age classes have a stronger *straightness percentage/longest branch* relationship than younger age classes. The old Riseholme arboretum specimens have an $R^2 = 0.33$, which is as low as most of the juvenile trees. The strength of the negative relationship between *straightness percentage and longest*

branch varies between species and age class. In the oak, 53% of the stems were totally straight (*straightness percentage* = 100%). In the juvenile sycamore, there was a significant cubic relationship (R^2 = 0.71, P<0.001) between *straightness percentage* and *longest branch*. 42% of the stems were totally straight (*straightness percentage* = 100%). In the nine year old ash at Mulgrave, 22% of the stems were totally straight (*straightness percentage* = 100%). In the old trees at Riseholme only 3% of the stems were totally straight (*straightness percentage* = 100%).

Another element to consider with Figure 5.4 is that a third data swarm exists. This can be seen at the top left of the graph where *straightness percentage* is 100 percent. This third cluster of data is shown to better effect in Figure 5.5.

Figure 5.5 Relationship between height and longest branch when straightness percentage is 100%.



$R^2 = 0.65$, F Stat = 347.15, $P < 0.0001$

Mean confidence limits shown at 95%

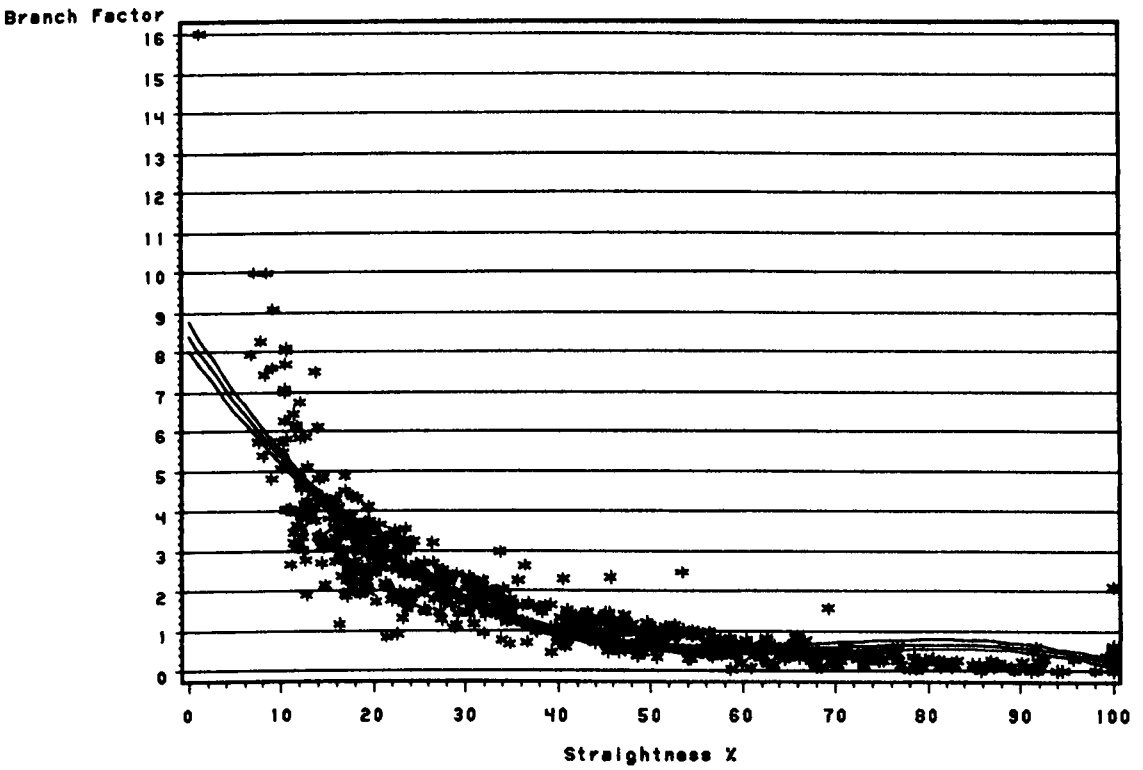
In Figure 5.5 *height* is plotted against *longest branch.* It should be noted that *straightness percentage* is 100% for every tree. To put it another way, *height* data is the same as *straight length* data. *Longest branch* varies when *straightness percentage* is 100%. When *straightness percentage* is 100 percent, increases in *longest branch* are related to increases in *height.*

These effects are due to the relationship between *height* and *longest branch.* Attempts to assess the relationships between branch length and stem straightness must take account of size related differences.

5.3.3 Relationships between branch factor and straightness percentage

The relationship between *branch factor* and *straightness percentage* for all trees in the study is illustrated in Figure 5.6.

Figure 5.6 Cubic relationship between branch factor and straightness percentage for all trees in the study



$R^2 = 0.82$ P< 0.0001 F Stat = 1152.06

Mean confidence limits shown at 95%

There is a negative exponential relationship between *branch factor* and *straightness percentage*. It is expressed as a cubic relationship because of the high numbers of trees with totally straight stems (*straightness percentage* = 100%). This, in effect, skews the relationship from the quadratic to the cubic. As *branch factor* decreases *straightness percentage* increases.

The horizontal reference line where *branch factor* =1 illustrates that branch factors less than 1 are associated with *straightness percentages* greater than 40%. *Straightness percentages* greater than 40% are associated with *branch factors* that are

less than 1. *Straightness percentages* greater than 40% are associated with *branch factors* that are 1 or less than 1.

Thus where *straightness percentage* = 20 *branch factor* = 3.0
where *straightness percentage* = 30 *branch factor* = 2.0
where *straightness percentage* = 40 *branch factor* = 1.0
where *straightness percentage* = 50 *branch factor* = 0.6
where *straightness percentage* = 60 *branch factor* = 0.5

Figures are accurate within 95% confidence limits

In effect, *branch factor* of about 1 can be regarded as a threshold point between trees with good stem straightness characteristic and those with poor stem characteristics.

The relationship between *branch factor* and *straightness percentage* for each site is illustrated in Table 5.7. Very strong negative exponential relationships exist for each site.

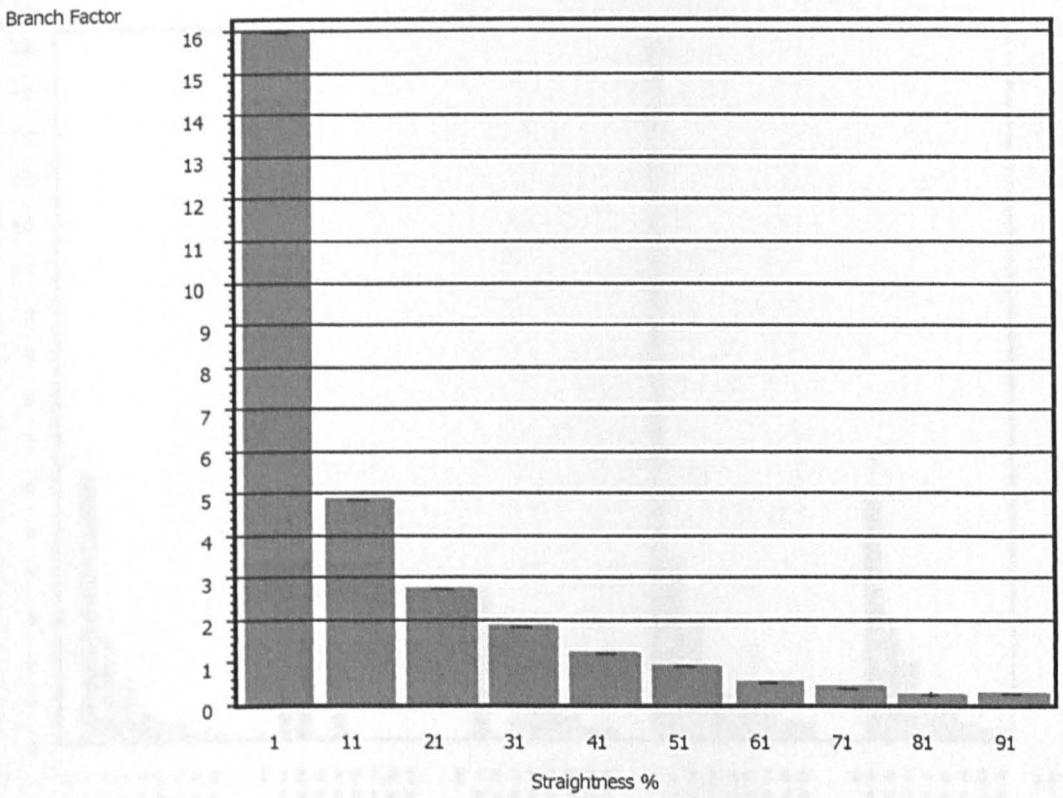
Table 5.7 Relationships between branch factor and straightness percentage

Species	R^2	P<	F Stat	Model Equation
sweet chestnut	0.86	0.0001	948.50	Cubic
3 year old oak	0.84	0.0001	123.78	Cubic
4 year old sycamore	0.84	0.0001	38.65	Quadratic
7 year old ash	0.73	0.0001	167.74	Quadratic
Yarborough ash & sycamore	0.90	0.0001	113.11	Cubic
Riseholme arboretum	0.82	0.0001	39.75	Cubic
All	0.82	0.0001	1152.06	Cubic

In sweet chestnut, where *branch factors* were less than 1, *straightness percentage* was typically greater than 50%. Where *branch factor* was less than 0.4, *straightness percentage* was typically greater than 80%. 26% of the stems were totally straight (*straightness percentage* = 100%).

Figure 5.7 shows the distribution of *branch factor* and *straightness percentage,* for all trees in the study. The rudiments of quality classes can be seen. Low *branch factors* are associated with straighter trees. There are ten midpoints identified in the bar chart. These represent *straightness percentage* classes arranged in increments of 10%. The numbers of midpoints can be adjusted to take account of any alternative *straightness percentage* classes.

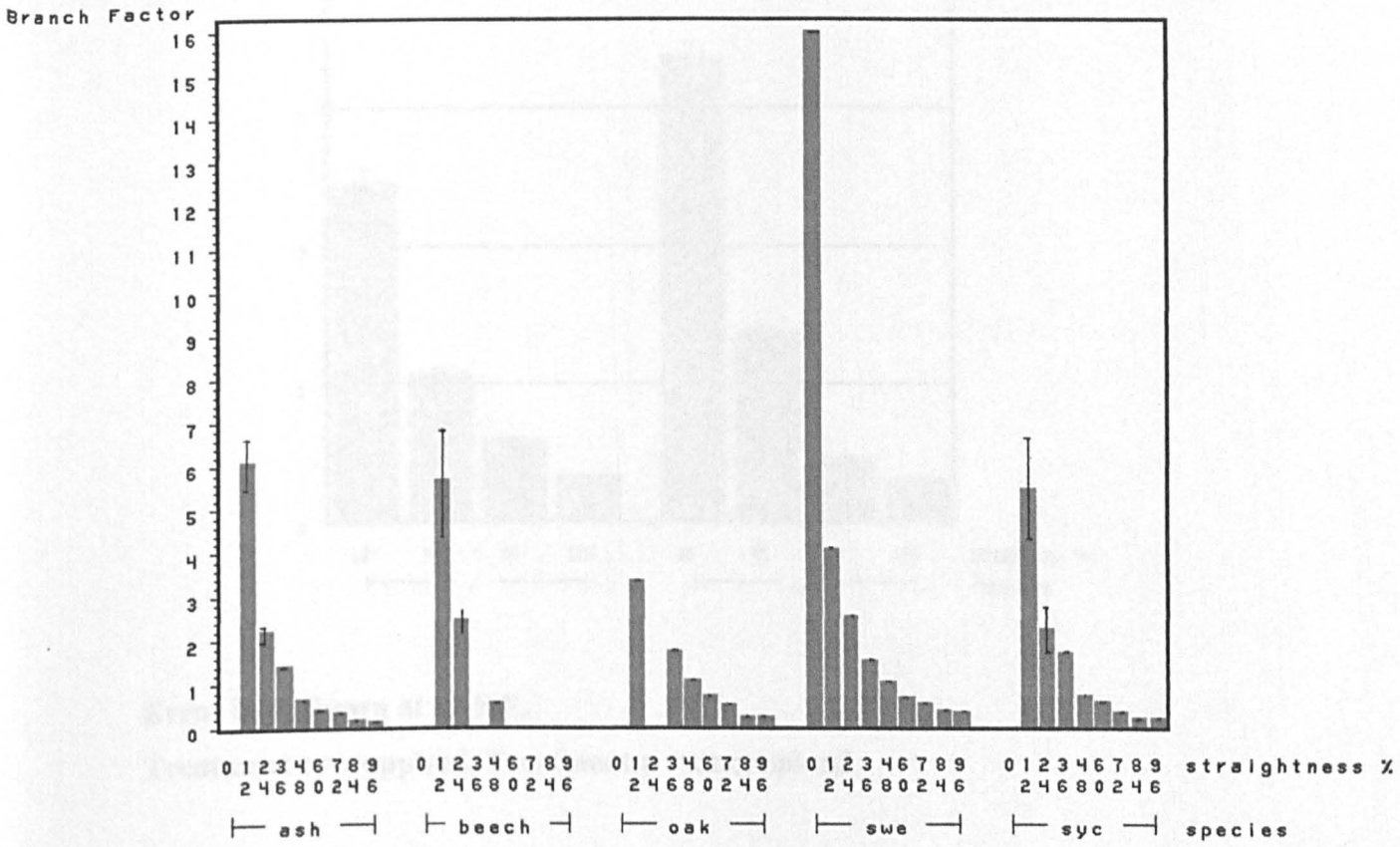
Figure 5.7 Distribution of mean branch factor and straightness percentage for all trees in the study



Error bars shown at ±2 S.E.

The distribution of *branch factor* and *straightness percentage* by species is illustrated in Figure 5.8. Quite large errors occur in species with small sample numbers such as sycamore, N=46 and beech, N=14 but the relationships are robust in species where the sample number is high such as ash, N=153 and sweet chestnut, N=469. The *branch factor/straightness percentage* relationship is consistent between species.

Figure 5.8 Comparison of branch factor and straightness percentage by Species



Error bars shown at ±2 S.E.

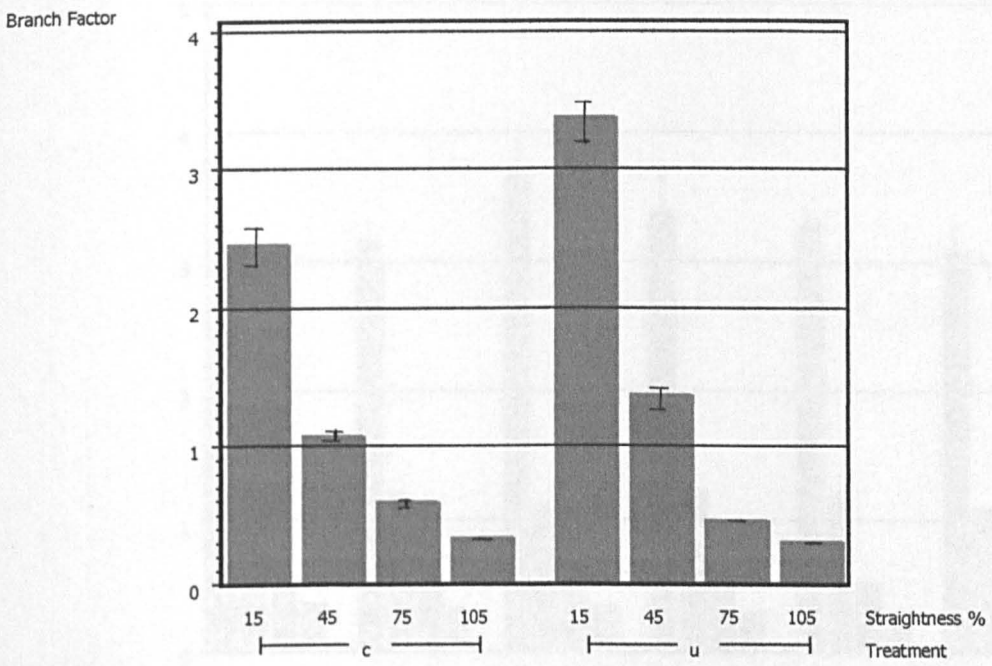
Key to *straightness percentage* – Figures should be read top to bottom

Thus 1, 12, 24, 36, ...96

This principle is extended in Figure 5.9. A comparison is made between trees that were coppiced and trees that were uncoppiced The shaded areas represent the

distribution of *branch factor* against *straightness percentage*. There is very little difference between the coppiced and uncoppiced trees. For example, *branch factors* of approximately 0.3 are associated with *straightness percentages* of 100% in both the coppiced and uncoppiced trees. In effect, the *branch factor/straightness percentage* relationship remains constant irrespective of coppice treatment.

Figure 5.9 Distribution of branch factor and straightness percentage by coppice treatment in juvenile sweet chestnut



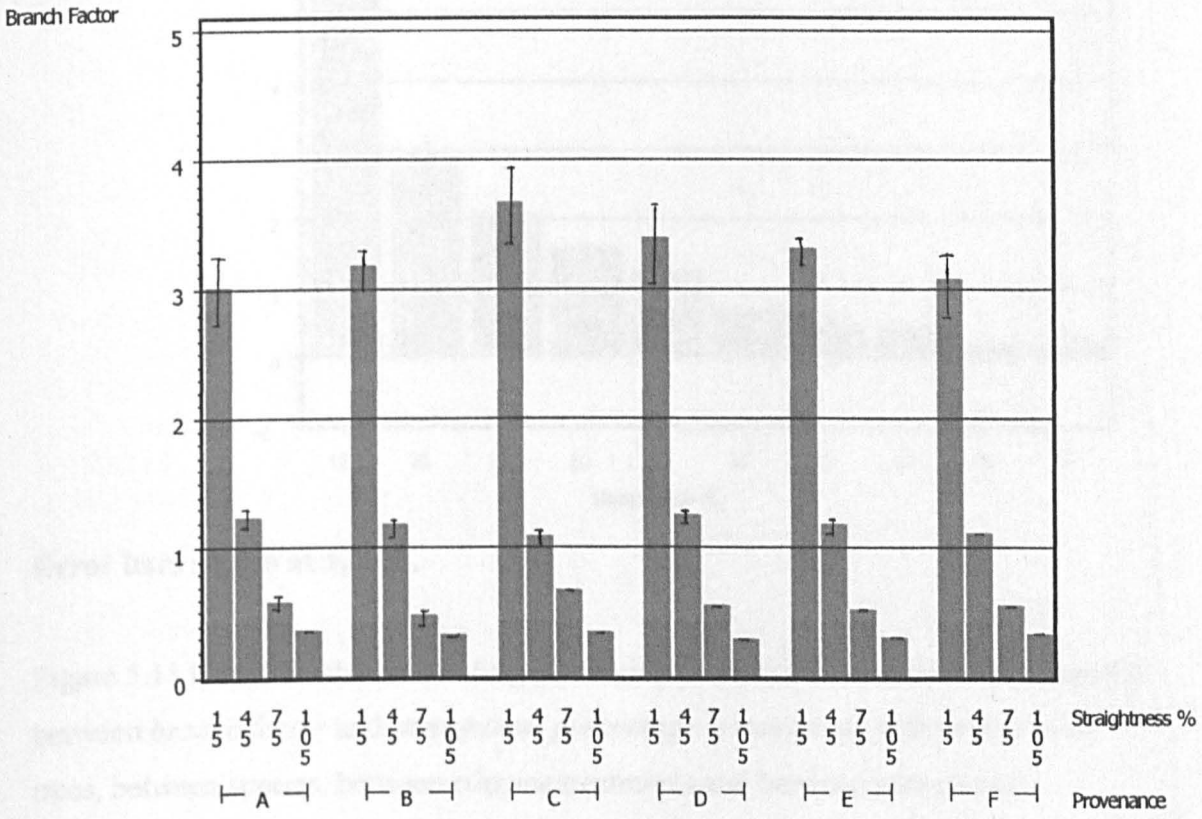
Error bars shown at ±2 S.E.

Treatment c = coppiced, Treatment u = uncoppiced

Mean *straightness percentage* is expressed as midpoints. There are no values of *straightness percentage* greater than 100%. The relatively large amount of error observed in the coppiced trees, where mean *straightness percentage* = 15%, is due to very low numbers of trees existing in this class.

Figure 5.10 illustrates the distribution of *branch factor* and *straightness percentage* relative to tree provenance. There are no significant differences, $P<0.001$, in the relationship between *branch factor* and *straightness percentage* as a result of provenance.

Figure 5.10 Distribution of branch factor and straightness percentage by provenance in juvenile sweet chestnut

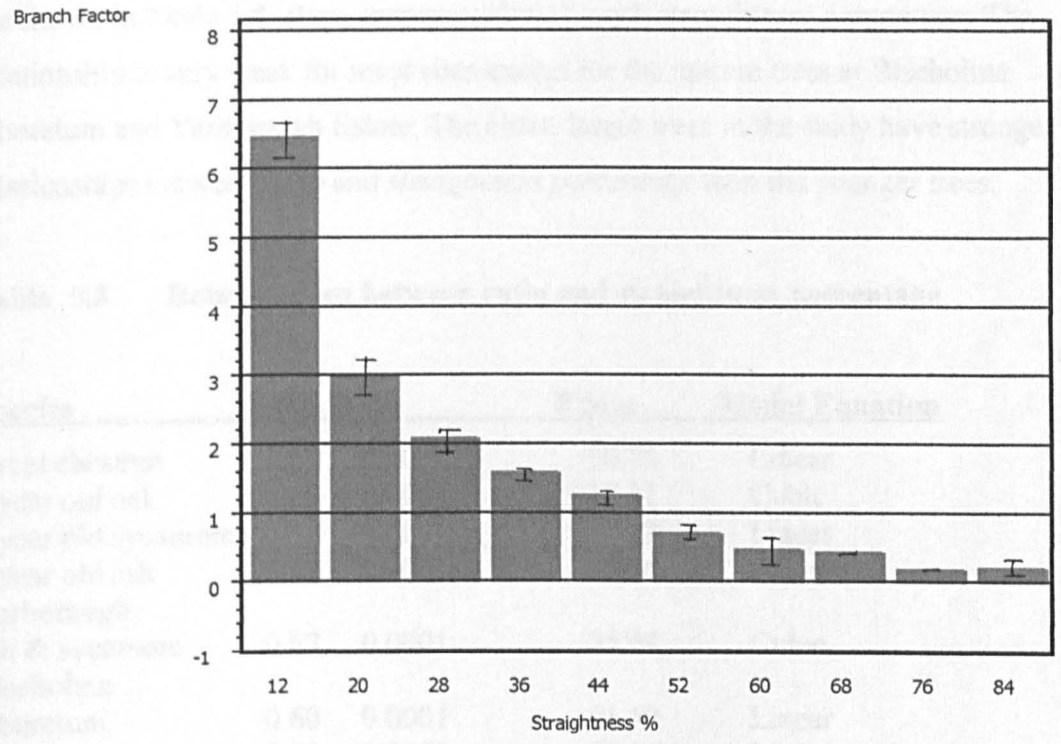


Error bars shown at ±2 S.E.

Key to *straightness percentage* – Figures should be read top to bottom

Thus 15, 45, 75, 105

Figure 5.11 Distribution of branch factor and straightness percentage in trees with heights greater than four metres



Error bars shown at ±2 S.E.

Figure 5.11 illustrates that in tree *heights* ranging from 4 to 33 metres the relationship between *branch factor* and *straightness percentage* is consistent with results in all trees, between species, between coppice treatments and between provenances.

Branch factor is a reliable predictor of *straightness percentage*.

5.3.4 Relationships between ratio and straightness percentage

The relationships between *ratio* and *straightness percentage* for all trees in the study are shown in Table 5.8. *Ratio* increases slightly with *straightness percentage.* The relationship is very weak for most sites except for the mature trees at Riseholme arboretum and Yarborough Estate. The older, larger trees in the study have stronger relationships between *ratio* and *straightness percentage* than the younger trees.

Table 5.8 Relationships between ratio and straightness percentage

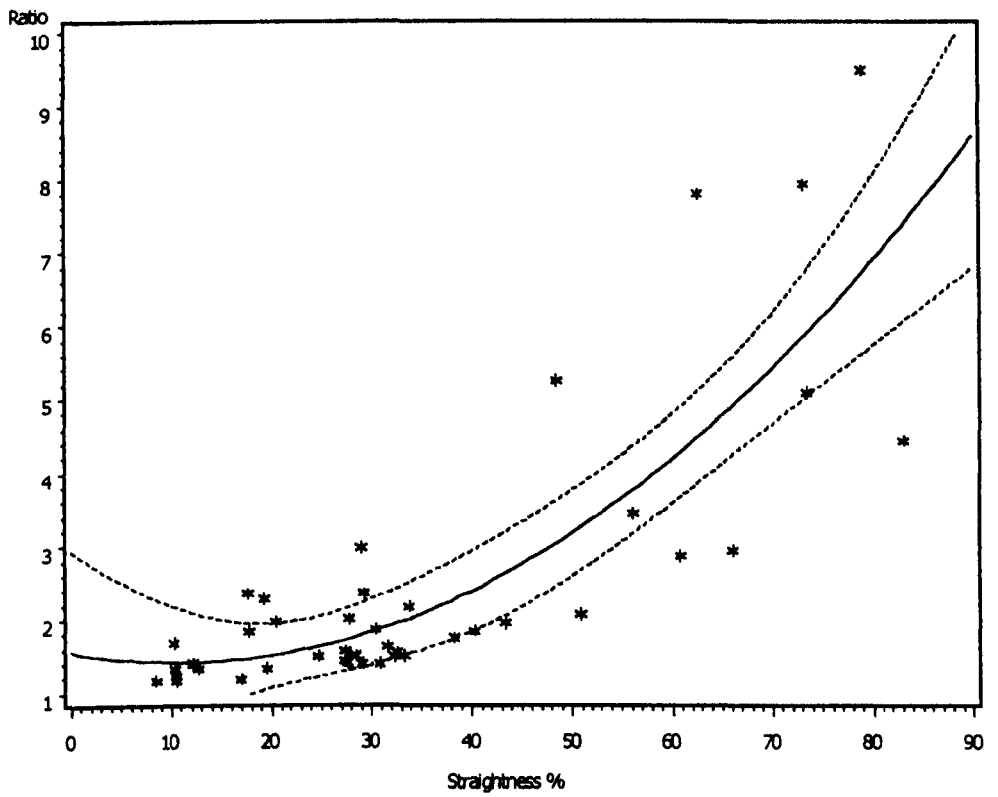
Species	R^2	P<	F Stat	Model Equation
sweet chestnut	0.09	0.0001	50.79	Linear
3 year old oak	0.20	0.0001	18.31	Cubic
4 year old sycamore	0.47	0.0001	20.99	Linear
7 year old ash	0.17	0.0001	24.66	Linear
Yarborough ash & sycamore	0.67	0.0001	25.94	Cubic
Riseholme arboretum	0.60	0.0001	41.50	Linear
All	0.14	0.0001	120.74	Linear

Many differences were apparent between the mature trees and the juvenile trees in the study. For example, none of the trees in the Yarborough population had *straightness percentages* of 100%.

As trees grow older more opportunities arise for stem straightness to decrease due to a variety of influences. Such things as insect attack, prevailing winds and silvicultural events can all affect stem development.

There is a significant cubic relationship between *ratio* and *straightness percentage* in the Yarborough ash and sycamore shown in Figure 5.12.

Figure 5.12 Relationship between ratio and straightness percentage in mature broadleaves from Yarborough Estate



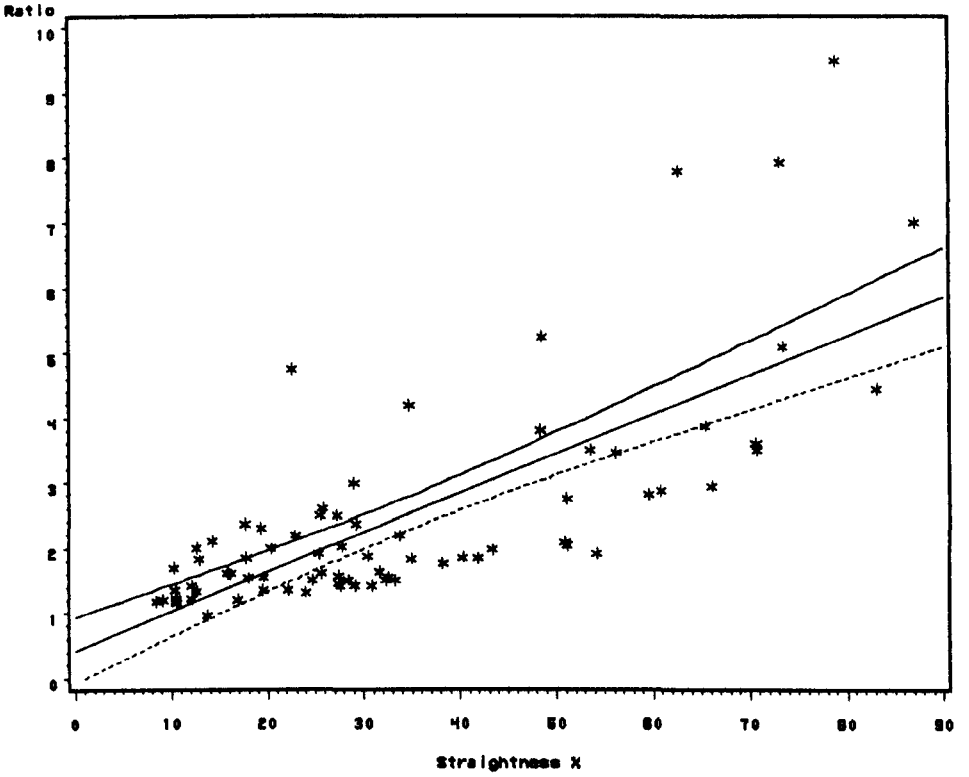
$R^2 = 0.67$, $P < 0.0001$

Mean confidence limits shown at 95%

The relationship between *ratio* and *straightness percentage* of all of the larger trees can be seen in Figure 5.13. There is a significant linear relationship ($R^2 = 0.55$,

$P<0.0001$) between *ratio* and *straightness percentage* in trees with *heights* greater than 4 metres,

Figure 5.13 Relationship between ratio and straightness percentage in trees greater than 4 metres in height

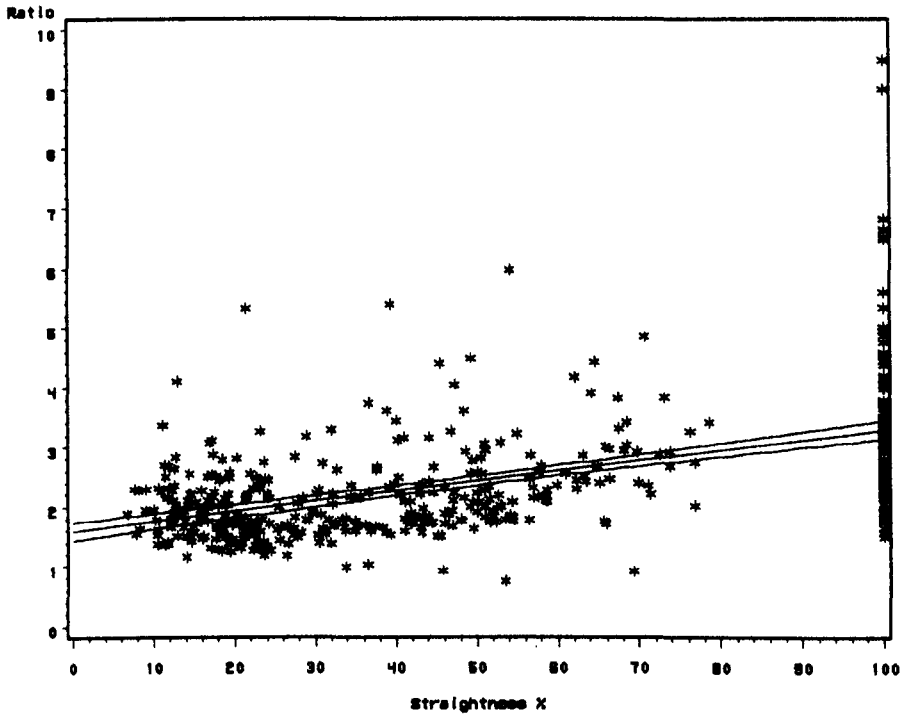


$R^2 = 0.55$, $P<0.0001$

Mean confidence limits shown at 95%

This can be compared with the results for sweet chestnut shown in Figure 5.14.

Figure 5.14 **Relationship between ratio and straightness percentage in juvenile sweet chestnut**



$R^2 = 0.09$, $P<0.0001$

Mean confidence limits shown at 95%

The weak relationship is characterised by a large variation in *ratio* where *straightness percentage* is 100%. There are also many outliers that do not conform to the model.

5.4 DISCUSSION

A figurative artist, or photographer, might reproduce a general impression of a tree that is instantly recognisable as a particular species. In Plate 5.1, for instance, ash is clearly distinguishable from sycamore. These typical mature examples of each species illustrate branch and stem characteristics that are repeated throughout the population.

In this chapter I have explored tree models based on comparisons between various morphological characteristics. There are significant negative relationships between *straightness percentage* and *longest branch.* The extent of this varies between species and age class. Weaker relationships occur, as in the case of the sweet chestnut, where there are many trees that have *straightness percentages* of 100%. The relationships between *height* and *straightness percentage* show that larger trees have proportionately longer branches than smaller trees.

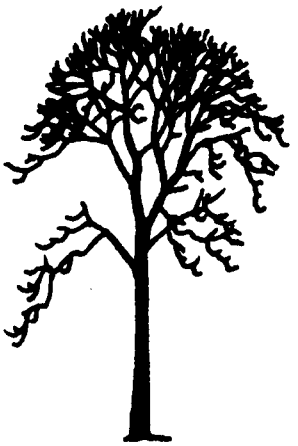
The exponential relationship between *branch factor* and *straightness percentage* is highly significant and very powerful. This relationship can be used to define quality (stem straightness) classes that are directly related to branch length (for example Figure 5.39). *Straightness percentage* is linked directly to *longest branch.* This has never been demonstrated before. Synonyms for *branch factor* might include such terms as Branch/Stem Index, Stem Form Index or Branch Index. Whatever the term chosen, it can be used to describe and predict stem form.

Branch factor = longest branch ÷ straight length. Longest branch is directly related to both *straight length* and *height* but inversely related to *straightness percentage. Straight length* is also related to *height* and *straightness percentage*. Previous studies of branch architecture have recognised interrelated morphological characteristics (Arbor, 1950; Harper, 1977; White, 1979; Wilson, 1989; Buck-Sorlin and Bell, 2000) but attempts to assess straightness have often been inconsistent and simplistic (Barnes & Gibson, 1986; Barrett & Mullin, 1968). The trees studied here show that the proportionality of morphological characteristics is fundamental to describing tree growth.

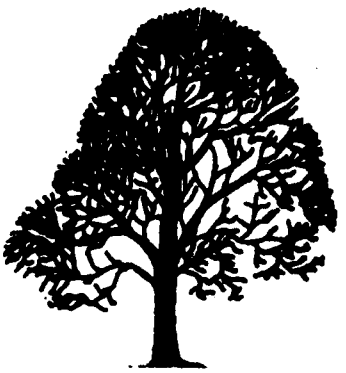
The relationship between the *height/longest branch ratio* and *straightness percentage* is far less convincing. Only the mature trees have a strong relationship. *Ratio = height ÷ longest branch. Height* is related to *longest branch* and *straight length* but negatively related to *straightness percentage.* In the juvenile trees there is a large variation in *ratio* where *straightness percentage* is 100%. Further work is required to find out why this is the case.

Many coniferous species are able to produce straight stemmed specimens with large differences in relative branch size. This is achieved because branching habits are usually symmetrical (Sporne, 1967). If long branches do occur, they are usually present on all sides of the tree. The overall form of the tree remains balanced. In these studies the mature broadleaved species did not have symmetrical branching habits. Many of the trees were open grown with uneven crowns that were typical for the species, Plate 5.1. Some juvenile trees seemed to have crowns that were more regular, in effect, symmetrical. The question arose, could the extent of crown symmetry be responsible for the poor relationship between *ratio* and *straightness percentage* in juvenile trees? It was necessary to study crown symmetry in juvenile trees in the context of stem straightness.

Plate 5.1 Typical form of mature ash and sycamore



Fraxinus excelsior



Acer pseudoplatanus

Phillips (1978)

6 CHAPTER SIX: THE EFFECTS OF BRANCH SYMMETRY AND LENGTH ON STEM FORM IN JUVENILE OAK

6.1 INTRODUCTION

In Chapter Five I demonstrated how stem straightness was related to branch length. The relationship between the *height/longest branch ratio* and *straightness percentage* was highly significant only in the mature trees. Casual observations during the studies described in Chapter Five suggested that the many of the crowns of juvenile broadleaves seemed to be symmetrical compared with older specimens. In this chapter I investigate the possible relationships between crown symmetry and stem straightness.

6.1 MATERIALS AND METHODS

6.2.1 Experimental design

In this chapter I used the Latin square designed experimental area containing juvenile oak. This area is described fully in Chapter Three. The layout of the design can be seen in Figure 3.1.

6.2.2 Measurements taken

a) Height

Height was assessed by measuring the height of the tree from ground level or root collar, whichever is higher, to the top of the leading shoot or bud (Hamilton, 1975).

b) *Straight Length*

Straight length is described as the length of straight stem, to the point where the main stem becomes indistinguishable or springs into the crown. A stem is considered straight until a bend or kink causes an angular deviation. Slight bowing is acceptable.

c) Longest branch

For reasons of economy and practicality I decided to minimise the number of measurements of branches on any one tree. Measurements of every branch include assessments of sub-branches. Each individual measurement is prone to error because decisions have to be made, in each case, where to measure from and where to measure to. As branches become smaller these decisions become more subjective.

I assumed that if branch length were related to stem straightness then all branches would probably have an influence but it was likely that long branches would have more influence than smaller branches. Long branches exert more leverage on the stem than short branches and they usually have larger diameters at the axil. It was logical to measure the length of the *longest branch* on each tree because such a branch would probably be more influential than lessor branches. This novel approach could always be abandoned if it proved to be irrelevant. *Longest branch* is defined as the length of the *longest branch* of a tree measured from the axil to the tip of the branch.

d) Crown symmetry

Symmetry has been described as a balanced arrangement of 'parts' about a dividing line or axis (Little *et al.*, 1933). The most thorough and time-consuming method of assessing crown symmetry is to assess the length and position of every branch about the main stem, which would form the axis. Another approach is to select branches or 'parts' having the most influence on symmetry and making the assessment based on the main stem as dividing line.

I decided to assess crown symmetry by using the main stem of the tree as the dividing line and the *longest branch* as one of the 'parts'. The *longest branch* on the tree would, by definition, have more influence on symmetry than lesser, shorter branches. If the *longest branch* on the tree were opposed by a branch of equal, or almost equal length, then the tree crown would be considered symmetrical. Measurements were made to determine symmetry. In the results section asymmetrical crowns are reported as 0, symmetrical crowns are reported as 1.

6.2.3 Treatments

No specific new treatments were applied but comparisons of tree performance could be made based on the sub-plot treatments applied in Chapter Three. Thus, one third of the trees were coppiced immediately following planting on site. One third of the trees were coppiced immediately after planting and then again after the first growing season. One third of the trees were left uncoppiced. These were the controls. Main plot treatments were tree spacings of 1.0m, 1.2m and 1.8m.

6.2.4 Statistical analysis

Principal component analysis was used to explore relationships between variables. Highly related variables were then analysed using generalised linear models.

6.3 RESULTS

The variables analysed using principal component analysis are shown in Table 6.1. Eigenvalues can be seen in Table 6.2. The original correlations are not shown. The number of eigenvalues considered worthy of study was assessed using the *Latent Root Criterion* approach (Guttman, 1954; Cliff, 1988). The first seven eigenvalues were selected. The component structure can be seen in Table 6.3.

Table 6.1 Variables analysed using principal component analysis

Variable	Description
Area	Main plot number
Treat	Coppice treatments
Spacing	Spacing treatments
MR	Main row effects within the Latin Square
MC	Main column effects within the Latin Square
SR	Sub-plot row effects
SC	Sub-plot column effects
TR	Tree row effects
TC	Tree column effects
Height	*height*
SL	*straight length*
LB	*longest branch*
Sym	Crown symmetry (either 0 or 1)
Stems	Number of stems per tree
Comp	Interspecies competition from natural regeneration (either 0 - no or 1 - yes)
SP	*straightness percentage*

Table 6.2 Eigenvalues of the correlation matrix in oak

Eigenvalue	Difference	Proportion	Cumulative	
1	2.61447260	0.65063663	0.1634	0.1634
2	1.96383596	0.08750482	0.1227	0.2861
3	1.87633114	0.50857112	0.1173	0.4034
4	1.36776002	0.30503029	0.0855	0.4889
5	1.06272974	0.01973452	0.0664	0.5553
6	1.04299522	0.00831792	0.0652	0.6205
7	1.03467730	0.05430140	0.0647	0.6852
8	0.98037590	0.01885593	0.0613	0.7464
9	0.96151997	0.02856754	0.0601	0.8065
10	0.93295243	0.22332331	0.0583	0.8649
11	0.70962912	0.10326659	0.0444	0.9092
12	0.60636253	0.12631517	0.0379	0.9471

Table 6.3 Principal component structure in oak

Factor Pattern

	Factor1	Factor2	Factor3	Factor4
AREA	-0.43536	-0.58436	0.66189*	-0.09143
TREAT	0.23413	-0.34633	-0.06032	0.58760*
SPACING	-0.03326	-0.10721	0.19223	-0.12530
MR	-0.44338	-0.62916*	0.57889	-0.12833
MC	-0.24309	0.29850	0.47683*	0.45893
SR	-0.09755	0.03596	-0.07965	-0.07679
SC	0.12497	0.09495	0.21302	0.15550
TR	0.00851	0.01412	0.05030	0.11811
TC	0.03961	0.05893	0.13751	-0.07099
Height	-0.10126	0.65066*	0.49503	-0.25810
SL	0.75523*	0.18982	0.50517	-0.12715
LB	-0.59145*	0.55060	0.09453	-0.15000
Sym	0.61283*	-0.03352	0.12401	-0.37460
Stems	0.13042	-0.06206	0.06781	0.52680
Comp	-0.00488	0.45513	0.35832	0.44616
SP	0.87380*	-0.13166	0.32319	-0.00891

	Factor5	Factor6	Factor7
AREA	-0.01311	-0.00554	0.00229
TREAT	0.10525	0.07433	0.10137
SPACING	-0.06528	0.72410*	0.08113
MR	0.04423	-0.10601	-0.00556
MC	-0.36664	-0.07425	-0.03652
SR	-0.38301	0.03464	0.58701*
SC	0.16467	0.03094	0.50607
TR	-0.07214	0.19866	-0.63478*
TC	0.23288	-0.59476*	0.01821
Height	0.27382	0.08775	0.01401
SL	0.10768	-0.02034	-0.01999
LB	0.27233	0.11965	0.02067
Sym	-0.18980	0.14516	0.02154
Stems	0.57188*	0.22148	0.08490
Comp	-0.39138*	-0.05771	-0.05214
SP	-0.02437	-0.07155	-0.03258

The highest loading for each variable across each factor was marked with an asterisk.

In Factor 1 *straightness percentage* is strongly negatively related to *longest branch. Straightness percentage* is also strongly related to crown symmetry and *straight length.* Trees with straight stems are associated with short branches and symmetrical crowns. Factor 1 also indicates that there are relationships between growth characteristics and geographical position within the experimental area. In effect, there are geographically determined fertility gradients.

In Factor 2 *height* is related to *longest branch* and competition from other trees.

Height is negatively related to main row position and related to area.
Factor 3 describes growth variables in relation to geographical position.

In Factor 4 the coppice treatments are slightly related to increases in tree competition and numbers of stems.

In Factor 5 numbers of stems are negatively related to competition from other trees.

Factors 6 and 7 are related to geographical position.

Table 6.4 Rotation of component structure in oak

	Factor1	Factor2	Factor3
AREA	-0.04449	0.98222*	0.04874
TREAT	0.26261	0.08933	-0.31852*
SPACING	0.05947	0.20819	0.05169
MR	-0.07213	0.95959*	-0.03893
MC	-0.11355	0.21849	0.56119*
SR	-0.12456	-0.03662	-0.01724
SC	0.17029	0.02944	0.20037
TR	0.02272	0.02061	0.04314
TC	0.07292	0.03683	0.13144
Height	-0.04906	-0.05158	0.82074*
SL	0.82990*	-0.08981	0.40595
LB	-0.61812*	-0.05582	0.52604
Sym	0.61019*	-0.14049	0.00025
Stems	0.15567	0.03252	-0.01305
Comp	0.03017	-0.05436	0.57593*
SP	0.93888*	-0.05042	0.03569

The highest loading for each variable across each factor was marked with an asterisk. Only the first three rotated factors contained significant loadings.

In Factor 1 *straightness percentage* is strongly negatively related to *longest branch* and strongly related to crown symmetry and *straight length*. *Straight length* is negatively related to *longest branch*. *Longest branch* is negatively related to symmetry.

Factor 2 is concerned with geographical position.

In Factor 3 *height* is related to tree competition, *longest branch* and geographical position. *Height* is negatively related to the coppice treatments.

A summary of the effects branch symmetry and coppice treatments can be seen in Table 6.5.

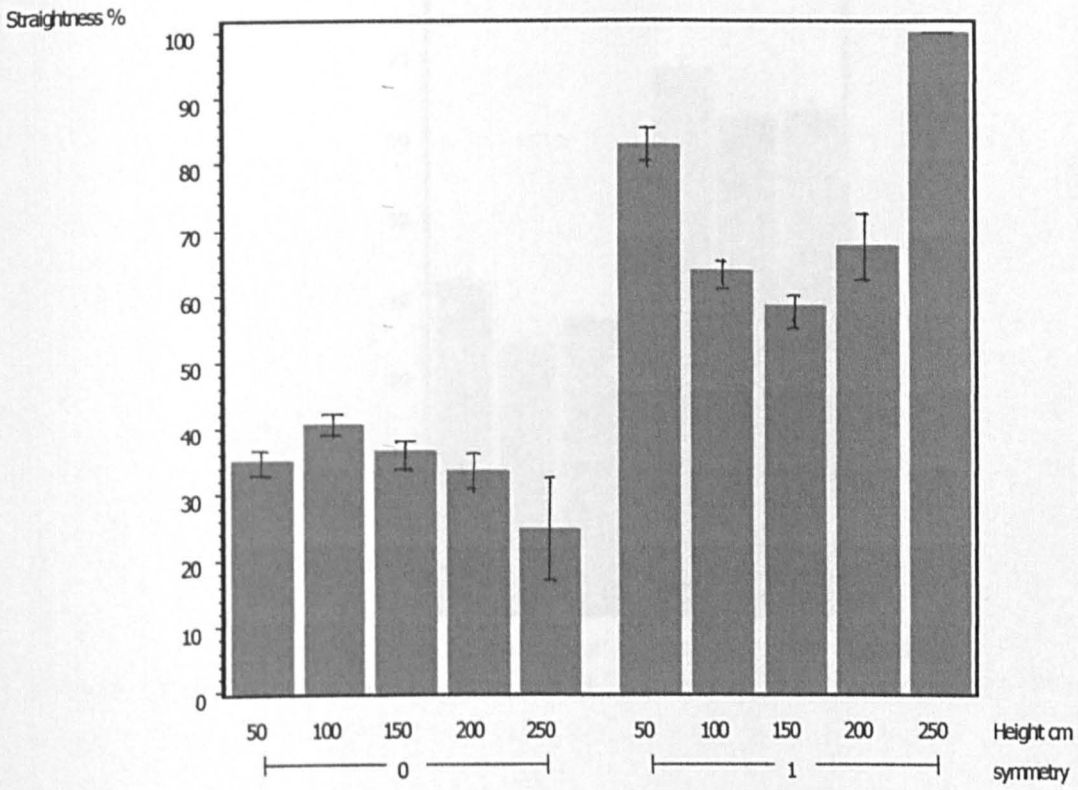
Table 6.5 The effects of symmetry and coppicing on tree growth in juvenile oak

Symmetry	TREATMENTS	Obs	Variable	Mean
0	0	115	height	146.23
			ratio	2.45
			straightness percentage	31.94
			longest branch	65.48
			straight length	46.55
	1	114	height	134.03
			ratio	2.66
			straightness percentage	36.88
			longest branch	56.03
			straight length	49.35
	2	107	height	122.44
			ratio	2.78
			straightness percentage	44.55
			longest branch	50.05
			straight length	54.14
1	0	81	height	149.64
			ratio	3.30
			straightness percentage	54.82
			longest branch	51.17
			straight length	81.77
	1	65	height	146.24
			ratio	3.78
			straightness percentage	63.22
			longest branch	46.01
			straight length	94.53
	2	61	height	126.31
			ratio	3.78
			straightness percentage	68.75
			longest branch	36.16
			straight length	86.93

Tree *height* is slightly less in asymmetrical trees than in symmetrical trees. Tree *height* declines slightly as a result of the coppice treatments. *Ratio* is higher in symmetrical trees than in asymmetrical trees. *Ratio* also increases as a result of the

coppice treatments. Both *straight length* and *straightness percentage* are higher in the symmetrical trees than in the asymmetrical trees. Increases in *straight length* and *straightness percentage* are also associated with the coppice treatments. Asymmetrical trees have longer longest branches than symmetrical trees. The mean length of the *longest branch* declines as a result of the coppice treatments. Mean *longest branch* was 57cm in the uncoppiced trees compared with 50cm in the trees coppiced once and 43cm in the trees coppiced twice (F Value = 16.01, $P < 0.0001$). Mean *longest branch* in the asymmetrical trees 57cm compared with 42cm in the symmetrical trees (F Value = 53.50, $P < 0.0001$)

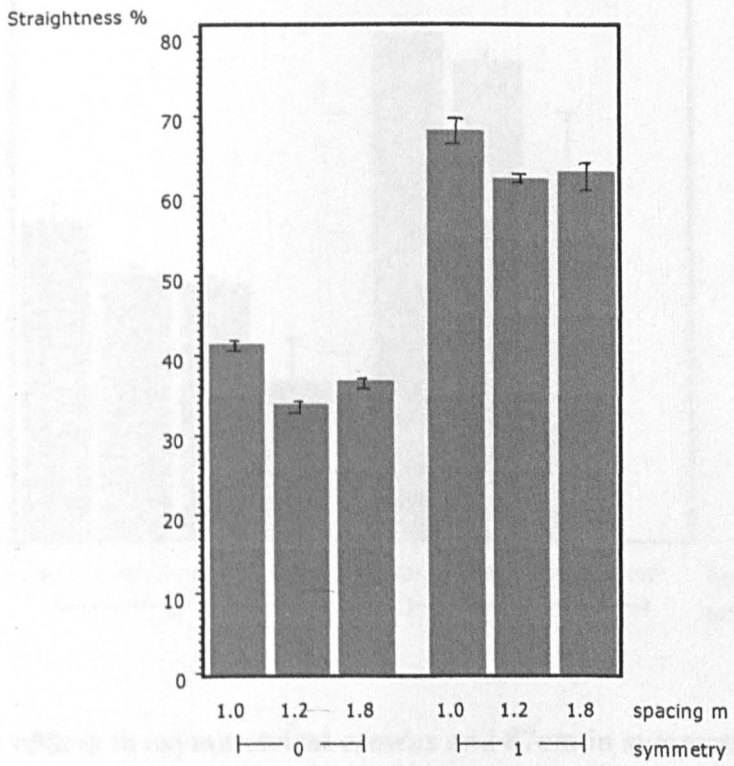
Figure 6.1 Bar chart showing straightness percentage by height in oak trees with asymmetrical and symmetrical crowns



Straightness percentage=37% in asymmetrical crowns and 64% in symmetrical crowns, F Stat = 137.57, $P < 0.0001$. Error bars shown at ±2 S.E.

Figure 6.1 shows the relationship between *straightness percentage* and *height* in trees with asymmetrical and symmetrical crowns. *Height* classes are expressed as a mean value. Error bars are large where mean *height* is 250 cm in the asymmetrical trees because of the small number of trees in this class. For each *height* class, *straightness percentage* is substantially greater in trees with symmetrical crowns than trees with asymmetrical crowns. Mean *straightness percentage* in trees with asymmetrical crowns is 37% compared with 64% in trees with symmetrical crowns, F Stat = 137.57, $P < 0.0001$. There is no difference in *height* between trees with asymmetrical crowns and trees with symmetrical crowns.

Figure 6.2 Bar chart showing straightness percentage by tree spacing in oak trees with asymmetrical and symmetrical crowns

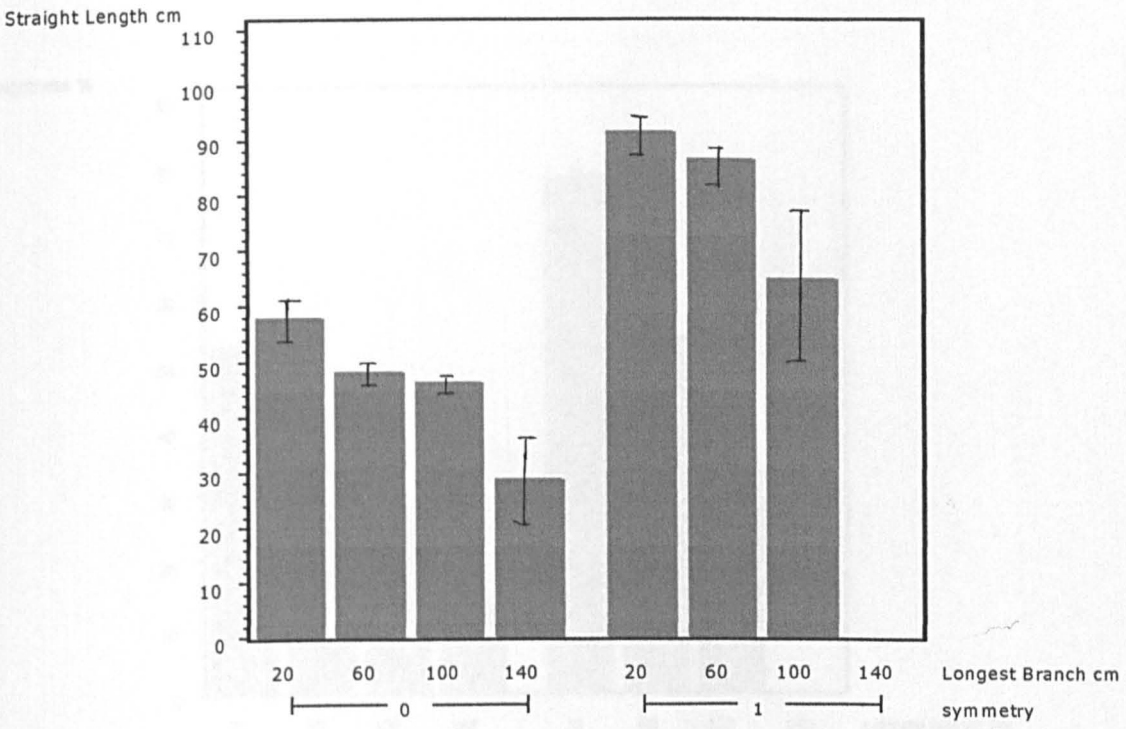


Error bars shown at ±2 S.D.

Straightness percentage=37% in asymmetrical crowns and 64% in symmetrical crowns, F Stat = 137.57, $P < 0.0001$. Error bars shown at ±2 S.E.

The relationship between *straightness percentage* and tree spacing in trees with asymmetrical crowns and trees with symmetrical crowns can be seen in Figure 6.2. For each tree spacing, *straightness percentage* is substantially greater in trees with symmetrical crowns than trees with asymmetrical crowns. There are no significant differences in *straightness percentage* as a result of tree spacing.

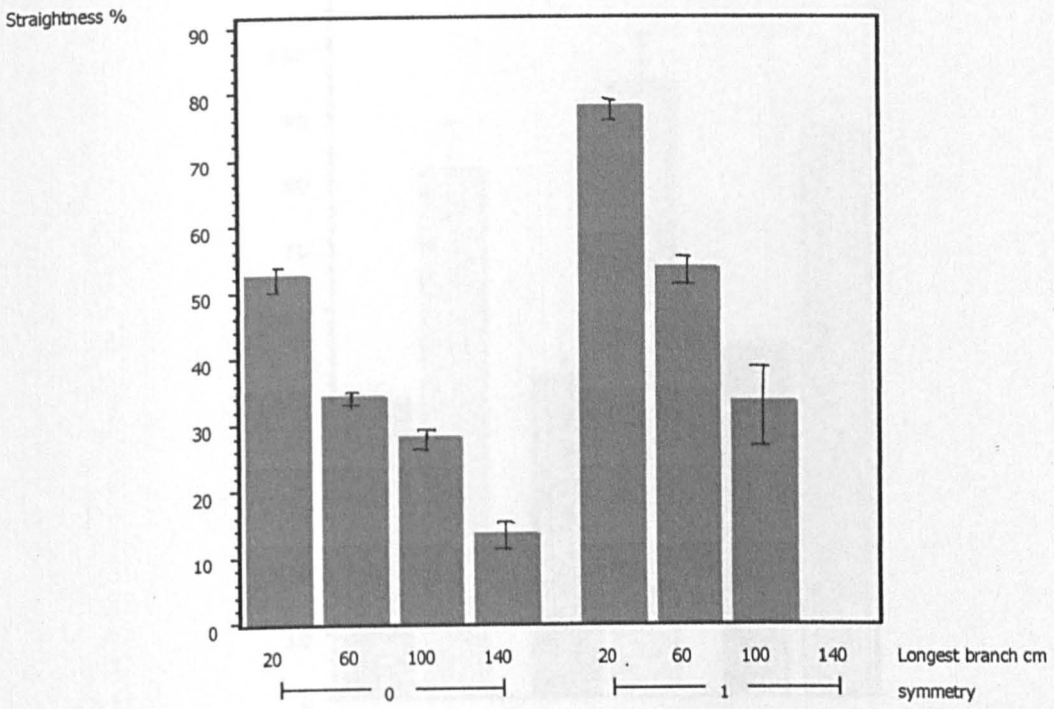
Figure 6.3 Bar chart showing straight length by longest branch in oak trees with asymmetrical and symmetrical crowns



***Straight length* =50cm in asymmetrical crowns and 87cm in symmetrical crowns, F Stat = 102.92, $P < 0.0001$. Error bars shown at ±2 S.E.**

The relationship between *straight length* at different levels of longest branch in trees with asymmetrical crown and trees with symmetrical crowns can be seen in Figure 6.3. For each *longest branch* class, *straight length* is substantially greater in trees with symmetrical crowns than trees with asymmetrical crowns. Mean *straight length* in trees with asymmetrical crowns is 50cm compared with 87cm in trees with symmetrical crowns, F Stat = 102.92, $P < 0.0001$. There are no significant differences in *straight length* as a result of *longest branch.*

Figure 6.4 Bar chart showing straightness percentage by longest branch in oak trees with asymmetrical and symmetrical crowns



***Straightness percentage*=37% in asymmetrical crowns**

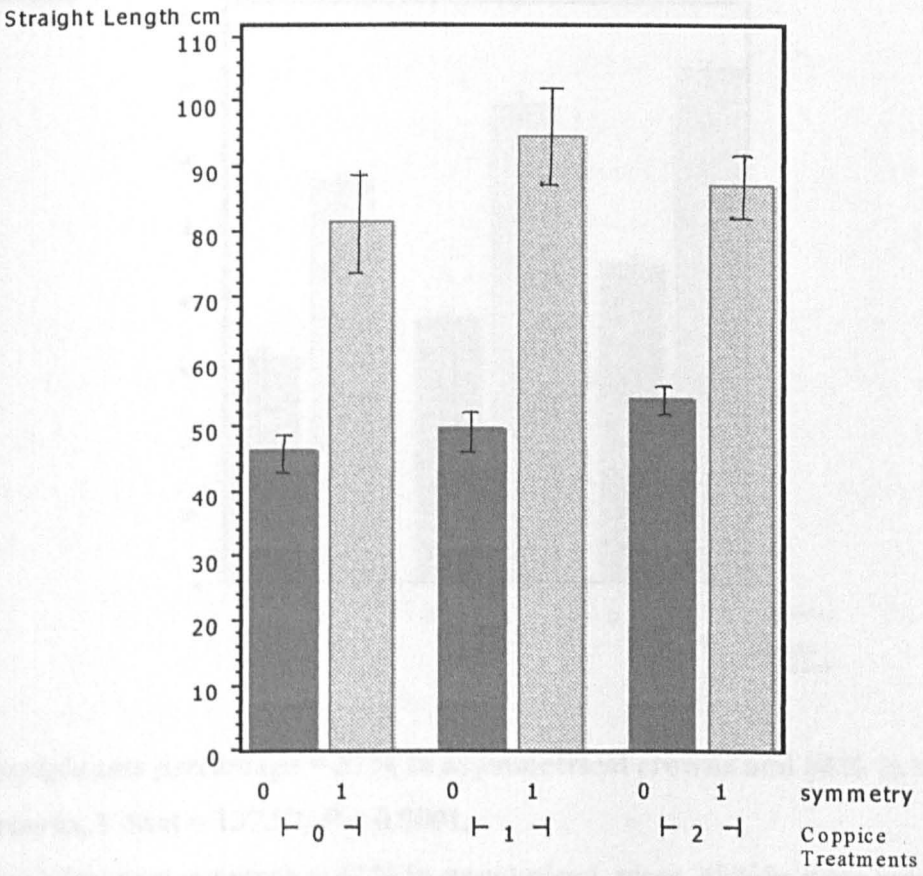
64% in symmetrical crowns, F Stat = 137.57, $P < 0.0001$.

***Straightness percentage* x *longest branch* negative relationship, $R^2 = 0.40$, $P < 0.0001$, F Stat = 3.06.**

Error bars shown at ±2 S.E.

The relationship between *straightness percentage* and *longest branch* in trees with asymmetrical crowns and trees with symmetrical crowns can be seen in Figure 6.4. For each *longest branch* class, *straightness percentage* is substantially greater in trees with symmetrical crowns than trees with asymmetrical crowns. As straightness percentage increases, longest branch decreases, $R^2 = 0.40$, $P < 0.0001$, F Stat = 3.06.

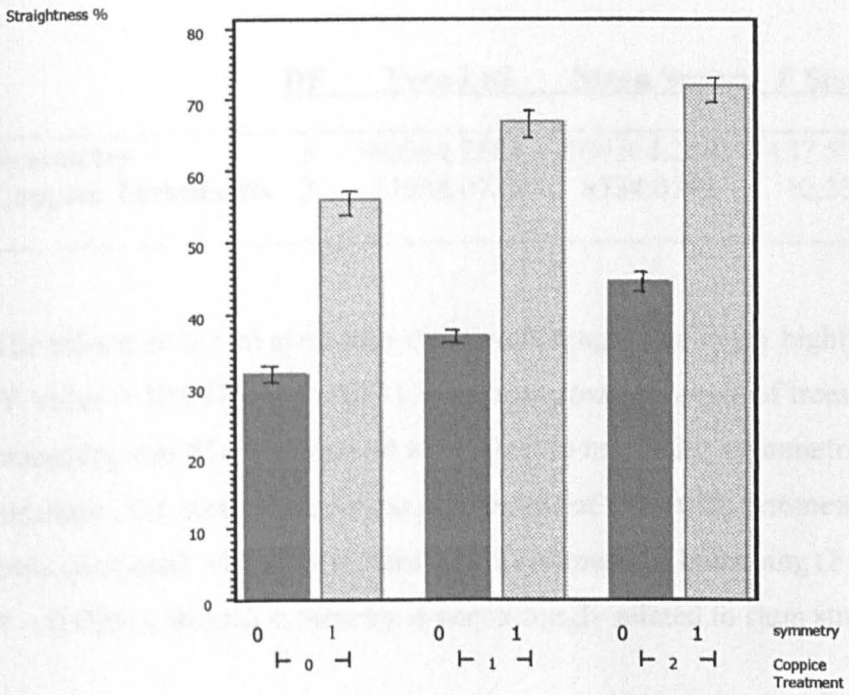
Figure 6.5 Bar chart showing straight length by crown symmetry in oak trees with coppice treatments



***Straight length* =50cm in asymmetrical crowns and 87cm in symmetrical crowns, F Stat = 102.92, $P < 0.0001$. Error bars shown at ±2 S.E.**

The relationship between *straight length* and crown symmetry at different levels of coppice treatment is shown in Figure 6.5. There are no significance differences of *straight length* as a result of the coppice treatments.

Figure 6.6 Bar chart showing straightness percentage by crown symmetry in oak trees with coppice treatments



***Straightness percentage* = 37% in asymmetrical crowns and 64% in symmetrical crowns, F Stat = 137.57, $P < 0.0001$.**

***Straightness percentage* = 42% in uncoppiced trees, 48%in trees coppiced once and 55% in trees coppiced twice, F Stat = 9.95, $P < 0.0001$.**

Error bars shown at ±2 S.E.

The relationship between *straightness percentage* and crown symmetry at different levels of coppice treatment is shown in Figure 6.6. There are significance differences in *straightness percentage* as a result of the coppice treatments.

An analysis of variance of the effects of symmetry and coppice treatments on straightness percentage can be seen in Table 6.6.

Table 6.6 Analysis of variance of straightness percentage by crown symmetry and coppice treatments

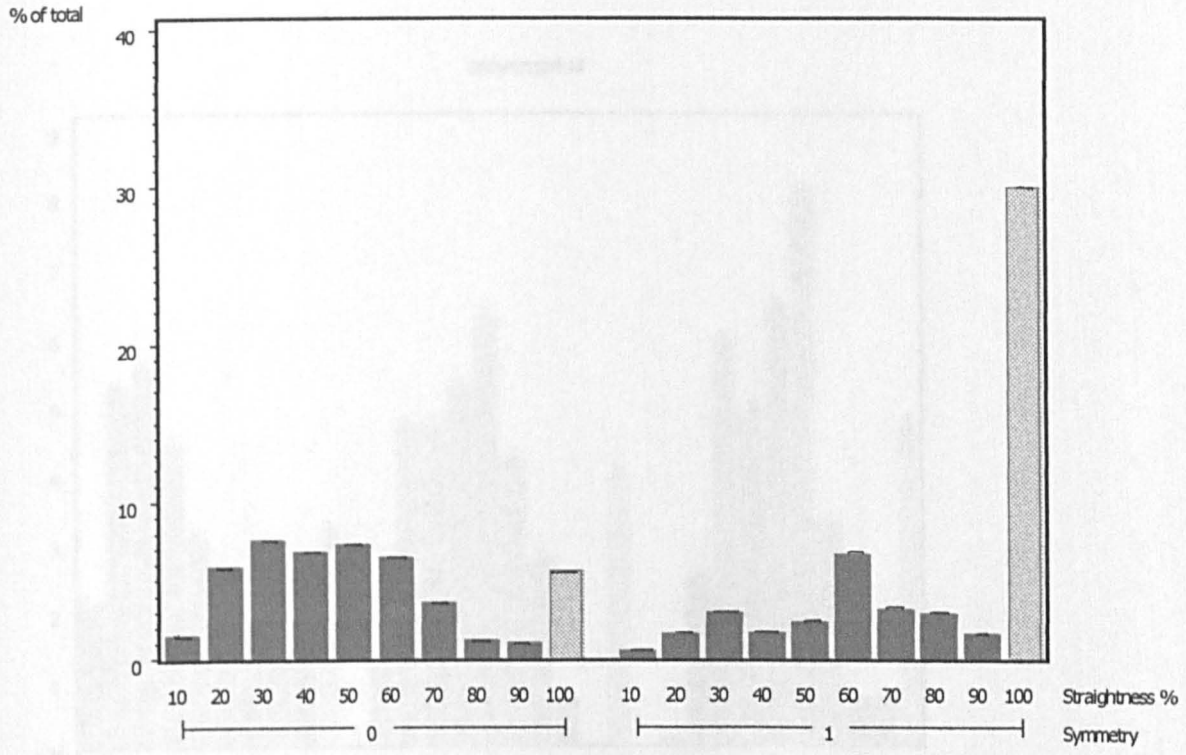
	DF	Type I SS	Mean Square	F Stat	P
Symmetry	1	100364.2581	100364.2581	137.57	<0.0001
Coppice Treatments	2	17068.0723	8534.0362	12.53	<0.0001

The effects of crown symmetry on *straight length* were very highly significant (F Value = 102.92, $P < 0.0001$). The mean *straight length* of trees with symmetrical branching was 87cm compared with 50cm in trees with asymmetrical branching. Similarly, the mean *straightness percentage* of trees with symmetrical branching was 64% compared with 37% in trees with asymmetrical branching (F Value = 137.57, $P < 0.0001$). Branch symmetry is very strongly related to stem straightness.

The mean length of the *longest branch* was 45cm in the trees with symmetrical branching compared with 57cm in the trees with a symmetrical branching (F Value = 38.31, $P < 0.0001$). Though the difference is significant, the differences in actual branch length are not particularly large.

The effect of crown symmetry on *height* was not significant. The mean *height* of the trees with symmetrical branching was 137cm compared with 135cm in trees with asymmetrical branching (F Value = 4.57, $P < 0.0631$). The actual differences in *height* were quite small.

Figure 6.7 Bar chart showing the distribution of straightness percentage in trees with asymmetrical and symmetrical crowns



Error bars shown at ± 2 S.E.

Hatched bar represents *straightness percentage* = 100%

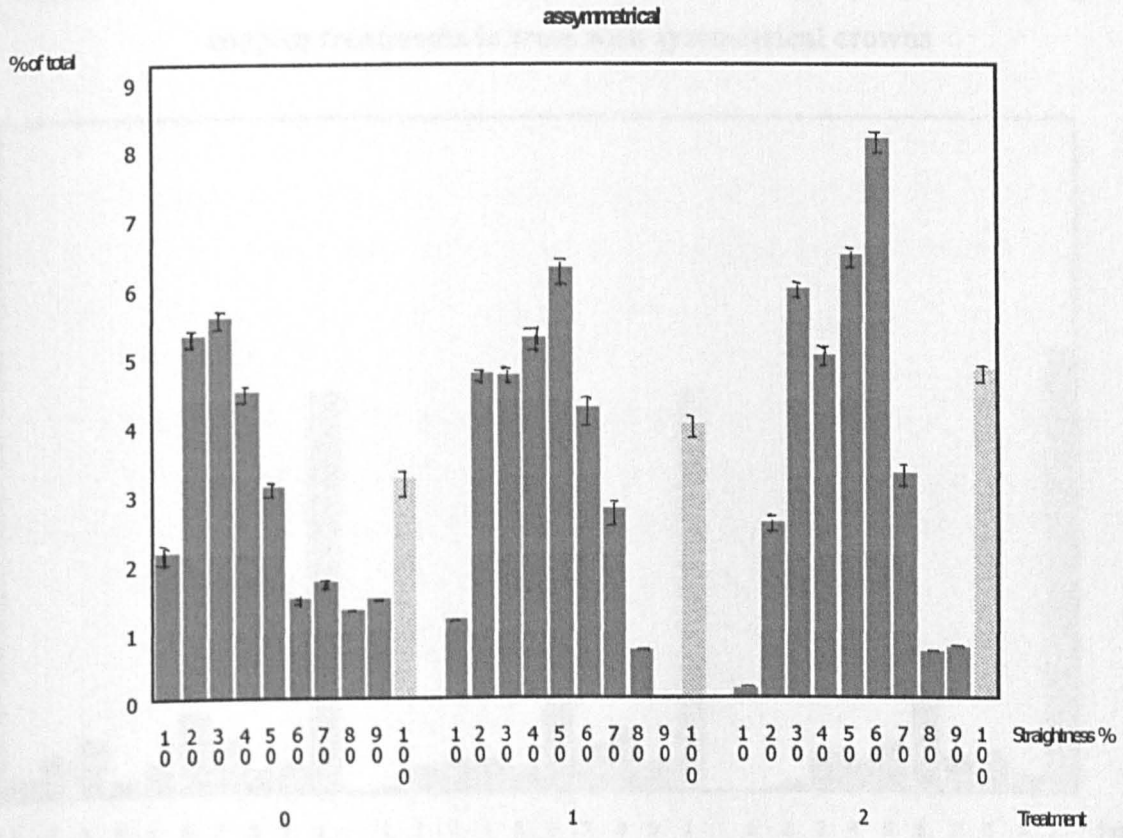
Symmetry 0 = asymmetrical

1 = symmetrical

Figure 6.7 shows the distribution of *straightness percentage* between trees with asymmetrical crowns and trees with symmetrical crowns. There is a dramatic improvement in the numbers of trees with *straightness percentages* of 100% when the trees have symmetrical crowns.

The distribution of straightness percentage by coppice treatments in trees with asymmetrical crowns can be seen in Figure 6.8.

Figure 6.8 **Bar chart showing the distribution of straightness percentage by coppice treatments in trees with asymmetrical crowns**



Error bars shown at ± 2 S.E.

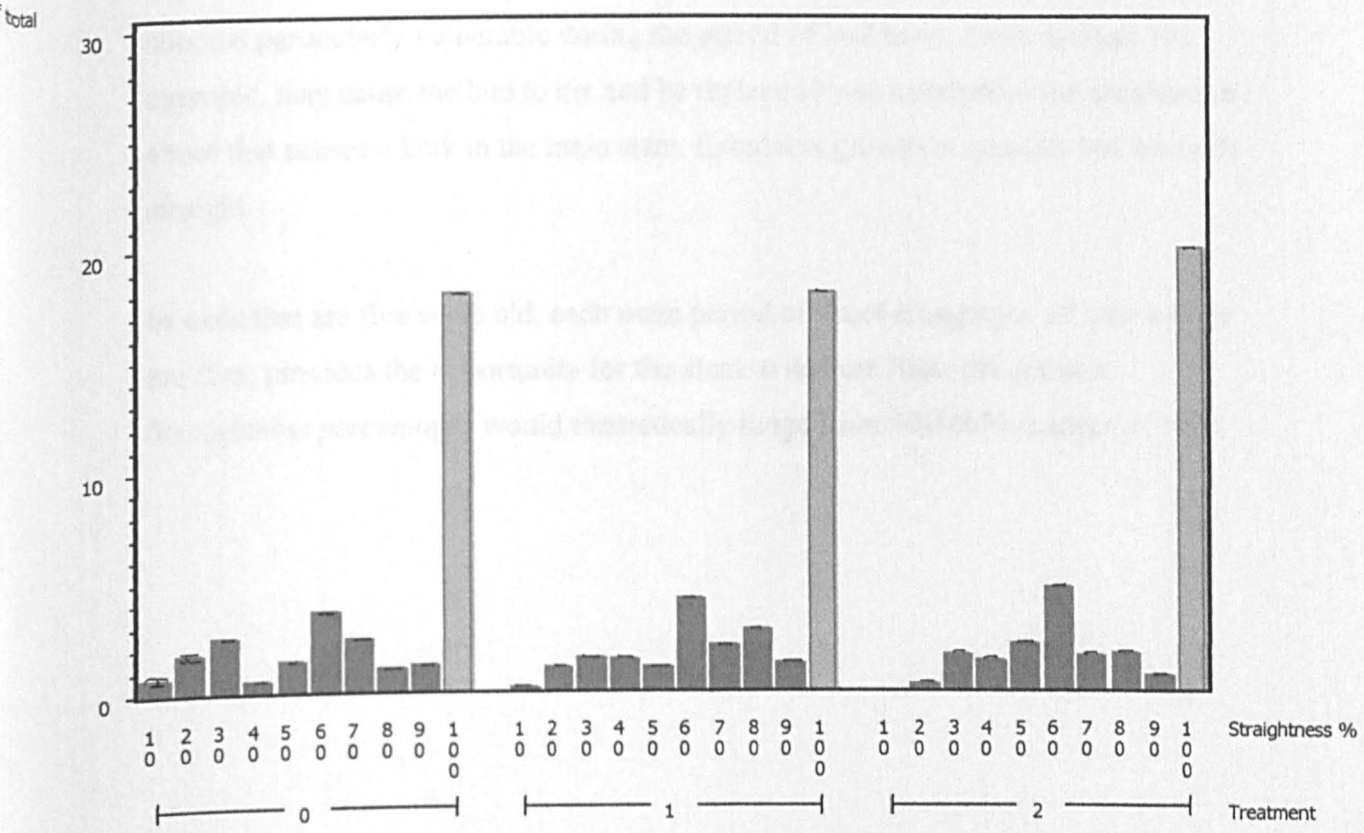
Hatched bar represents *straightness percentage* = 100%

Treatment 0 = uncoppiced, 1 = coppiced once, 2 = coppiced twice

There is a slight improvement in the numbers of trees where *straightness percentage* = 100% as a result of the coppice treatments. The distribution of *straightness percentage* in the uncoppiced trees is slightly skewed to the left compared with the trees in the two coppice treatments. It can be inferred from this that the generality of *straightness percentages* in the uncoppiced trees is lower than that of the coppiced trees. The distribution of *straightness percentage* peaks at 30% for the uncoppiced trees compared with 50% in the trees coppiced once and 60% in the trees coppiced twice.

These results can be compared with the distribution of *straightness percentages* by coppice treatments in trees with symmetrical crowns, Figure 6.9.

Figure 6.9 Bar chart showing the distribution of straightness percentage by coppice treatments in trees with symmetrical crowns



Error bars shown at ± 2 S.E.

Hatched bar represents *straightness percentage* = 100%

Treatment 0 = uncoppiced, 1 = coppiced once, 2 = coppiced twice

The distribution of *straightness percentage*, where *straightness percentage* is less than 100%, peaks at 60% in all three coppice treatments. There is only a slight difference in the numbers of trees that have *straightness percentages* of 100% as a result of coppice treatments.

Figures 6.7, 6.8 and 6.9 seem unusual in that they each contain bimodal distributions, one for trees where *straightness percentage* = 100% and another for the remainder of

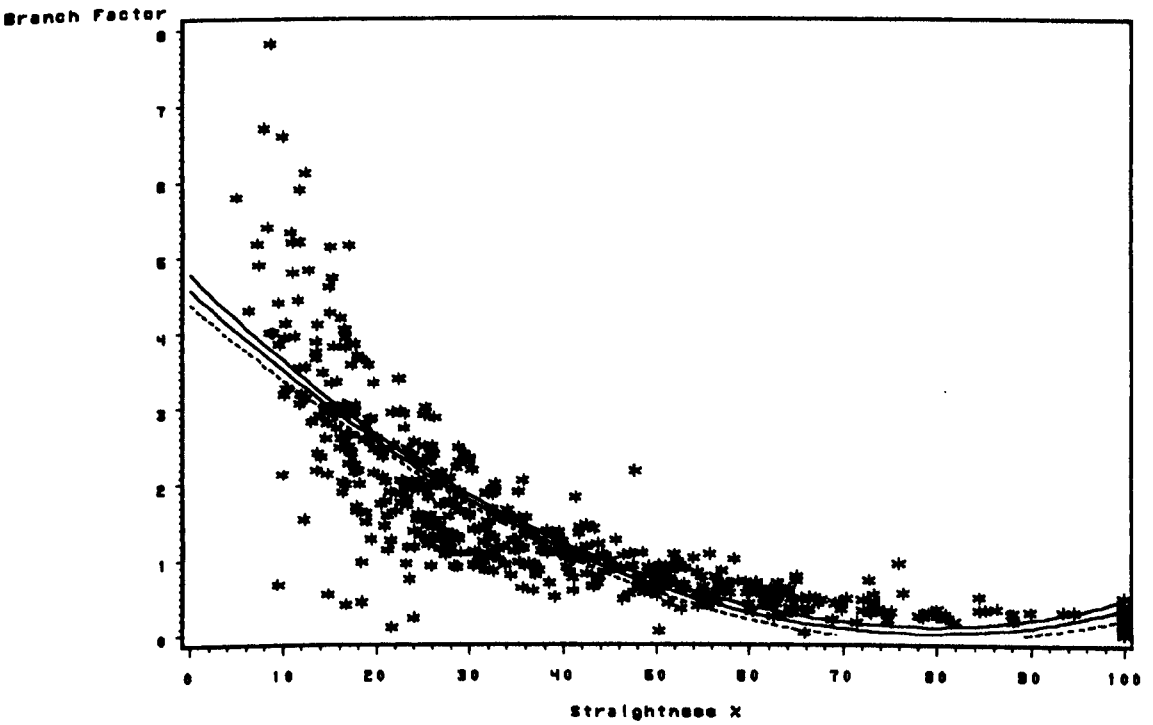
the trees. Why, for example, are there not more trees with a straightness percentage of 90%? The answer probably lies in the way in which tree shoots grow. Shoots elongate in bursts of straight growth, typified by early summer and lammas growth. The period of senescence is accompanied by a hardening off and stiffening the shoots. Wilson (1989) and Buck-Sorlin and Bell (2000b) refer to tree branches as extension units that are repeatable but also vulnerable to localised events. The bud of a leading shoot is particularly vulnerable during the period of bud burst. Frost damage, for example, may cause the bud to die and be replaced by an alternative that produces a shoot that causes a kink in the main stem. Extension growth is sporadic but typically straight.

In trees that are five years old, each main period of shoot elongation, of which there are five, provides the opportunity for the stem to deviate from straightness. *Straightness percentages* would theoretically range from 10-100% in steps of 10%.

The relationship between *branch factor* and *straightness percentage* is shown in Figure 6.10. There is a highly significant cubic relationship ($P<0.0001$, $R^2 = 0.77$, N= 568) between *branch factor* and *straightness percentage.* This compares well with results reported in Chapter Five where N=81.

The mean *branch factor* in trees with symmetrical branching was 0.91 compared with 1.73 in trees with asymmetrical branching (F Value = 59.09, $P < 0.0001$).

Figure 6.10 Relationship between branch factor and straightness percentage in juvenile oak in 2002



$R^2 = 0.77$ P< 0.0001 F Stat = 659.72

Mean confidence limits shown at 95%

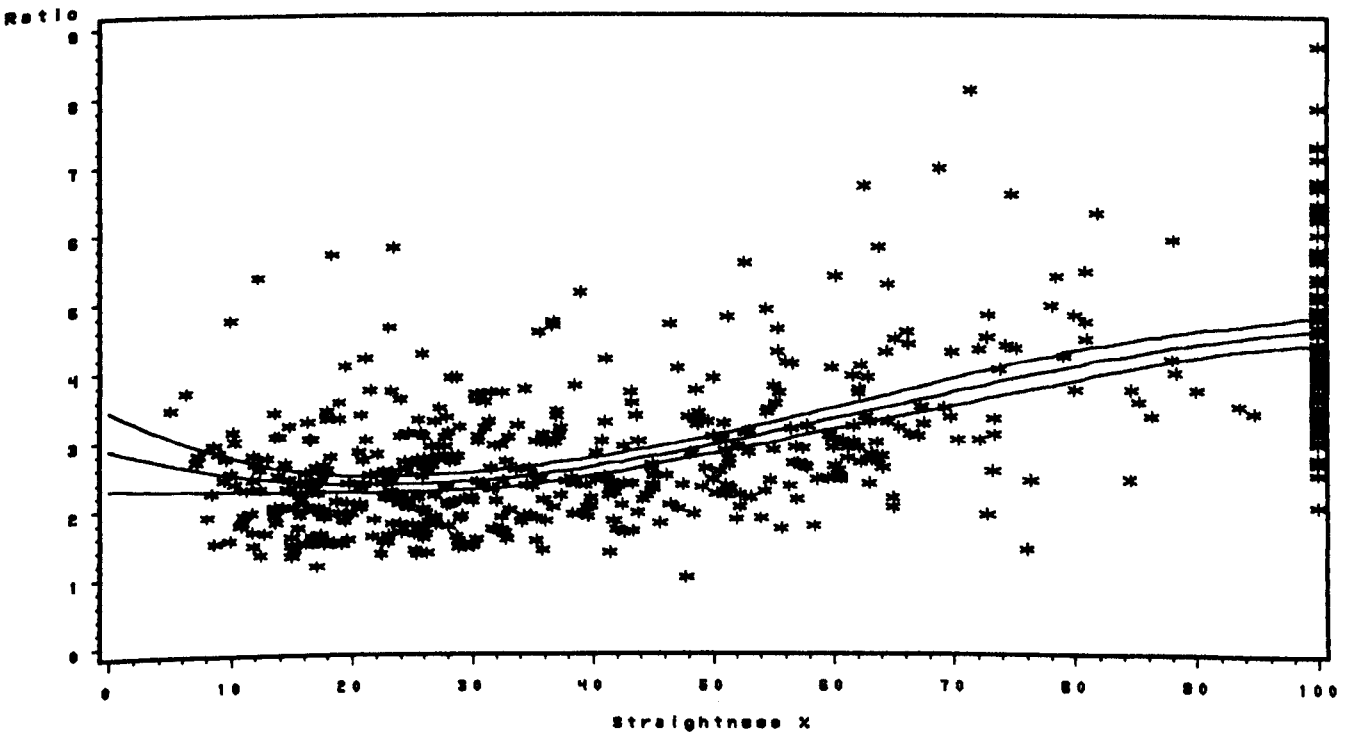
Branch factor can be used as a reliable index for describing *straightness percentage.* It relates two morphological characteristics together, *longest branch* and *straight length,* whose relationship which straightness percentage is remarkably consistent.

This relationship should be compared with that between *ratio* and *straightness percentage* shown in Figure 6.11.

There is a significant cubic relationship ($P<0.0001$, $R^2 = 0.41$) between *ratio* and *straightness percentage*. There are many outliers and it is clear that *straightness percentage* is not only related to *ratio* but to other factors.

The effect of crown symmetry on *ratio* was highly significant. The mean *ratio* of the trees with symmetrical crowns was 3.60 compared with 2.62 in the trees with asymmetrical crowns (F Value = 87.07, $P < 0.0001$).

Figure 6.11 Relationship between ratio and straightness percentage in juvenile oak in 2002



$P<0.0001$, $R^2 = 0.41$

Mean confidence limits shown at 95%

Ratio does not make as reliable an index of stem straightness as *branch factor*. *Ratio* describes the relationship between *height* and *longest branch*. *Branch factor* describes

the relationship between *longest branch* and *straight length.* The relationship described by *ratio* is focussed on the proportionality of characteristics that are size related. *Branch factor*, on the other hand is focussed on the interdependence between *straight length* and *longest branch*, which is identified in Factor 1 of the rotated principal component structure, Table 6.4.

6.4 DISCUSSION

In Chapter Five it was established that *branch factor* is closely related to *straightness percentage* (Figure 5.6). Similar results were found in this chapter (Figure 6.1). It was also evident, in Chapter Five, that *ratio* was strongly related to *straightness percentage* in mature trees but less so in juvenile trees. Similar results for juvenile trees are found in this chapter.

The summary of morphological characteristics seen in Table 6.1 shows clearly that in juvenile oak stem straightness is strongly related to crown symmetry. This is evident in assessments of both *straight length* and *straightness percentage*. *Height* is also related to crown symmetry but *longest branch* is inversely related to crown symmetry.

Trees with symmetrical crowns have straighter stems and shorter branches than trees with asymmetrical crowns. The positive effects of coppicing on tree growth are more evident on trees with asymmetrical crowns than trees with symmetrical crowns.

The coppice treatments had no effect on crown symmetry. The positive effects of coppicing on stem form were largely independent of the good stem form seen in the trees with symmetrical crowns.

The *height/longest branch ratio* is higher in symmetrical trees than in asymmetrical trees. This *ratio* also increases as a result of the coppice treatments. Trees with symmetrical branching have much better morphological characteristics that those in asymmetrical trees. Trees with symmetrical branching also have shorter branches.

It is clear from these experiments that the most important morphological characteristic that is related to stem straightness is a symmetrical branching habit. When trees have asymmetrical branching habits, the proportionality between the length of the *longest branch* and tree *height* becomes a good predictor of stem straightness.

The coppice treatments were responsible for a small decline in tree *height* but were responsible for improvements in stem straightness and reductions in branch length.

Spacing had no real effect on stem straightness in the coppiced trees but it was noticeable that the onset of canopy closure reduced branch length in all trees. As expected, between-tree-competition in the uncoppiced trees prevented further extensions of branch length near the base of the tree.

7 CHAPTER SEVEN: CONCLUDING REMARKS

7.1 INTRODUCTION

The research described here is both experimental and correlational. The experimental research involved the manipulation of tree shoot growth by coppicing. The effects of this were tested on growth variables such as *height*, *straight length*, *straightness percentage* and *longest branch*. The correlational research involved observations of relationships of morphological traits in broadleaved trees. Some of these trees had been manipulated as part of the experimental research but others had not been interfered with. In the discussion that follows, I have interpreted the results of both the experimental and correlational research in the context of causality, biological relevance and recommendations for future work.

7.2 DISCUSSION

One of the original objectives of these studies was to explore the concept of coppicing as a novel approach to the establishment of veneer quality timber crops. These studies demonstrate that coppicing causes straight stem regrowth in juvenile timber trees without the need for close spacing recommendations reviewed by (Savill and Spilsbury, 1991). This is a novel approach.

The improved straightness effects occur irrespective of tree spacing, provenance or original form. In effect, sow's ears are turned into silk purses, at least for a while. Not only is the mean stem straightness of a population of trees improved but also the proportion of totally straight trees is increased. These improvements in stem form gradually decline as new growing seasons produce new shoots but this decline is halted as the forest canopy begins to close and mutual competition restricts the growth of lateral branching. At this point all of the trees, both coppiced and uncoppiced, begin to favour growth from the leading shoot rather than the lateral branches. The beneficial effects of coppicing on stem straightness are therefore only required for the first five or six years or until the canopy begins to close.

Deformations or bends in tree stems are sometimes regarded as being of genetic origin. This may be the case but the dramatic improvements in stem form in the

juvenile oak show that normal growth traits can be temporarily suspended in response to rapid change, in this case coppicing. The response of shoot growth to rabbit damage in wild cherry show that natural forms of trauma can produce growth effect similar to those caused by coppicing. Kimmins (1997) argues that trees deploy adaptive strategies to optimise the available solar radiation. Open grown trees maximise branch production whereas trees competing for light maximise apical dominance. It is possible that species adaptability may be as important a factor as individual observable traits when determining the choice of phenotypes. Macdonald *et al.* (1983) and Emery *et al.*, (1994) observed significant compensatory plasticity of morphological characteristics, in relation to environmental heterogeneity, in the herbaceous perennial, *Stellaria longipes*. This species is extant in one form or other in much of north America. A better understanding of the adaptive strategies of tree species such as *Quercus robur*, which also enjoy a wide geographical distribution may yield useful information for tree breeders and silviculturists alike. A genetic predisposition for adaptation may be as important as a genetic predisposition for individual morphological traits (Emery *et al.*, 1994). Further work should be carried out into the evolutionary processes of broadleaved tree species. This could have benefits not only for foresters but also for scientists in general. For instance, studies of a range of British and European genotypes, managed under a selection of silvicultural systems, might provide valuable information about relationships between nature and nurture. This might help determine the objectives of tree geneticists. Studies of morphological traits in species at the edges of their geographical or topograhical distribution might provide an insight into evolutionary processes as well as an insight into variations in climatic conditions.

The investigations into the effects of coppicing led to an exploration of what determines the straightness of a tree stem. The coppice experiments demonstrated causation. The trees studied in these experiments followed rules of proportionality. Large trees had proportionately longer branches than small trees. When *height/longest branch* related effects were discounted, trees with straight stems had shorter branches than trees with stems that were not straight. Stem deformations, or bends, occurred when branches became disproportionately long compared with *height*. It is probable that long branches exert more leverage on the main stem than short branches because

of the effects of branch mass. In effect, long branches have larger knots and supporting woody structures at the axil than shorter branches, thus providing greater opportunities for the development of kinks and stem deformities. The integrity of the structures and systems that control tree form are dependent upon proportionality.

Branch length is of particular importance in these studies because it was observed in the coppicing experiments that the trees with comparatively short *longest branches* tended to have straighter stems than those with comparatively long *longest branches*. There was a causal relationship between the coppice treatments and improved *straightness percentage* and reduced *longest branch*.

The inverse relationship between *straightness percentage* and *longest branch* observed in the experimental research was similar to that found in the correlational research. In Chapter Six it can be seen that *straightness percentage* is strongly inversely related to *longest branch* and strongly related to crown symmetry and *straight length*. *Straight length* is also inversely related to *longest branch*. Does *straightness percentage* determine the length of the *longest branch* or is it the other way around? Does *straightness percentage* determine crown symmetry, or is it the other way around? It was not possible to determine causation in these studies. This may be achieved by biomechanical testing of branch leverage on stem characteristics. In these studies I was more interested in the existence of the relationship itself. It was established that coppicing produced these related effects but alternative successful strategies to maintain branch symmetry and limit branch length are liable to be rewarded by improved stem straightness. This was probably why the establishment high quality broadleaved crops at high initial planting densities in mainland Europe (Savill & Spilsbury, 1991) was so successful. Szymanski (1966, 1977, 1983, 1986, 1994, 1999) established innovative oak experiments in Poland around the southern Baltic Sea. These are now known as the 'clumping method of oak silviculture' (Ceitel and Szmyt, 2002). Typically, 45 oak seedlings were established in clumps of 33 cm x 33 cm, with up to 600 clumps per hectare. No further work or tending was carried out for at least 20 years. This is an extreme form of traditional methods of silviculture. The resulting straight, almost branchless poles were then progressively thinned out. The coppicing work in the studies described here is an innovative and successful attempt to induce apical dominance and to restrict branch length in young trees. The

restriction of branch length, by any means possible, as well as the maintenance of crown symmetry, should be among the main objectives of silviculturists. This is important not only to restrict knot sizes but also essentially to maintain stem straightness.

The concept of *branch factor* was developed to describe the relationship between *longest branch* and *straight length*. *Branch factor* is an objective tool that can be used to predict stem straightness and to rank trees in terms of quality. *Branch factor* was consistent within species over a range of age classes but there were slight differences between species. Further work could produce *branch factors* for individual species. Species related differences in *branch factor* would also provide evidence for reliable species related mathematical growth models. *Branch factor* is an ideal tool for silviculturists to monitor relationships between branchiness and stem straightness. For instance, maintaining *branch factors* at appropriate specified levels can ensure stem straightness.

These studies revealed certain problems that were difficult to overcome when assessing relationships between morphological characteristics in mature broadleaves. It is quite rare to find mature specimens that have not been subject to some form of silvicultural or arboricultural treatment that might artificially affect relationships. A wolf tree, for example, with a very bent and twisted stem may be high pruned to a point above these deformations. Subsequent assessments of *longest branch* might be misleading. Extreme examples of such trees were generally avoided in these studies. More innovation is required to maintain branch symmetry and to restrict branch length in older trees in order to produce straight, branch free boles suitable for use as veneer quality timber.

Many coniferous species are able to produce straight stemmed specimens with large differences in relative branch sizes. This is achieved because branching habits are usually symmetrical (Sporne, 1967). If long branches do occur, they are usually present on all sides of the tree. The overall form of the tree remains balanced. The trees in these studies did not always have symmetrical branching habits. The studies in the juvenile oak showed that branch symmetry was the most important factor that is related to stem straightness. Mature trees with large symmetrical crowns grow

vigorously with straight stems. When trees did not have symmetrical branching, the length of the longest branch is highly related to stem straightness. It is possible that the production of disproportionately long branches, in trees with asymmetrical branching habits, causes imbalances of physical loading on main stems, which in turn encourages deformations in the growth characteristics of main stems. Future biomechanical studies might explore this.

A population of young broadleaved trees will have a large proportion of individuals with symmetrical branching habits. Many of these trees will also have straight stems. As they get older most of the trees lose their branch symmetry and stem straightness diminishes. The stem straightness of trees with asymmetrical branching is closely related to the length of the *longest branch.* There was a much stronger relationship between *ratio* and *straightness percentage* in mature trees than that observed in juvenile trees. The use of *ratio* to monitor and control stem straightness in older trees is a realistic alternative to the use of *branch factor.*

Harmer (2000) observed that studies of branch production in young plants might enable simple, large scale screening of seed sources. The selection in favour of short branched and symmetrical individuals at the juvenile stages of growth, may be rewarded by mature specimens with small branches and straight stems.

Growing trees with symmetrical crowns will help ensure that stems are straight. Trees with asymmetrical crowns are so because one or more branches are substantially longer than the rest. This disproportionality of form in branching is also reflected as a disproportionality of stem form.

The research described here is an original and important contribution to the understanding of crown architecture and stem morphology in broadleaved tree species. The exploratory analysis of the data revealed relationships, both positive and negative, between morphological traits that were repeatable and predictable. Trees are logical structures with a logical architecture. This has important implications for silviculture, genetics and biological science in general.

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Publications and conferences

Cowell A.M. 2001. The effects of coppicing on the growth characteristics of juvenile oak trees. Conference proceedings - Nursery Production and Stand Establishment of Broad-Leaves to Promote Sustainable Forest Management, Rome, Italy 7th-10th May 2001. Abstract below.

ABSTRACT

The Effects of Coppicing on the Growth Characteristics of Juvenile Oak Trees

The establishment of high quality broad-leaved crops is normally achieved by planting in high densities. High planting densities promote apical dominance and restrict branch development. Planting at high densities is often avoided because of excessive costs. These investigations describe a novel approach to the establishment of broad-leaves that could reduce overall establishment costs and improve stem quality.

It is known that young oak trees, if damaged or cut, will reproduce vegetatively from dormant buds. The oak trees in these studies were cut back to ground level (coppiced) one year after planting. Their subsequent development was monitored for improvements in vigour and stem quality. The effect of initial planting density on tree growth was also monitored. Trees were planted at densities of 1.0m × 1.0m spacing, 1.2m × 1.2m spacing and 2.0m × 2.0m spacing. Preliminary results show that the incremental height growth of the coppiced trees one year after coppicing was almost three times that of the controls. The mean increment of the coppiced trees was 30.82cm while that of the controls was 10.08cm. The coppiced trees also grew straighter than the controls irrespective of planting density. The mean length of straight stem in the coppiced trees was 30.41cm while that of the controls was 22.08cm. The mean percentage straightness of the coppiced trees was almost 98.85% whereas the mean percentage straightness of the controls was 59.57%. Coppicing had

no effect on the total height of the trees. Coppicing inhibited branch production irrespective of planting density.

The coppicing of the oak trees, one year after planting, had a dramatic and positive effect on growth and vigour. Coppicing increased apical dominance and the trees grew much faster and straighter than the uncoppiced trees. Improvements in apical dominance and form were achieved in the coppiced trees without the use of high planting densities. The coppicing of juvenile broad-leaved trees could contribute to improvements in the quality of tree planting programmes without increasing planting densities and without increasing costs.

Conference Presentation

Cowell A.M. 2002. Predicting stem form from branch length and tree height in some broadleaved tree species. Management of Valuable Broadleaved Forests in Europe, Freiburg, Germany 5-9 May, 2002

ABSTRACT

Predicting stem form from branch length and tree height in some broadleaved tree species.

Stem straightness, branch length and height growth were studied in various age classes of *Acer pseudoplatanus, Fraxinus excelsior and Prunus avium.* Relative to tree height, the longest branch length on each tree was inversely proportional to stem straightness, $R^2 = 0.6037$, ($P < 0.0001$). In all species and ages, stem straightness was related to the ratio between the length of the longest branch and tree height. Stem straightness declined rapidly where stem lengths were less than three times the length of the longest branch. An analysis of outliers indicated that the length of the longest branch had less effect on the stem form of trees with symmetrical branch architecture than those with asymmetric branching. Further investigations revealed that branch

length is a reliable predictor of stem form in trees with asymmetric branching. The results are discussed in relation to pruning, tree spacing, silvicultural treatments and the selection of phenotypes.

Book Review

Book Title - Management of valuable broadleaved forests in Europe (Institute for Forest Growth at the University of Freiburg and the European Forest Institute)
Review of Chapter 3.2 - Genetics and tree breeding. Reviewed November 2002.

Appendix A

Sweet Chestnut Seed Origins

Ident	Location	Latitude	Longitude
SC90 (40) Lot 900	Bradford Estate, Salop	52.42N	02.21W
SC90 (30) Lot 900	Clytha Park, Gwent	51.45N	02.55W
SC90 (40) Lot 902	Eling Estate, Berkshire	51.28N	01.18W
SC90 (40) Lot 903	Hereford	52.04N	02.43W
SC90 (40) Lot 904	Longleat, Wiltshire	52.14N	02.14W
SC90 (40) Lot 905	Mottisfont, Hampshire	51.03N	01.31W